USING LUMINANCE FOR DESIGN AND EVALUATION OF ENERGY EFFICIENT AND SUSTAINABLE LUMINOUS ENVIRONMENTS TO SUPPLEMENT CURRENT ILLUMINANCE-BASED DESIGN CODES

BY

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ABSTRACT

Illuminance and illuminance-based metrics have been adopted in lighting design and field measurement over the past century to support the notion that the primary function of lighting is for task performance and visibility. However, illuminance and illuminance-based metrics, which are commonly measured on target planes, are only a portion of the lighting metrics necessary to quantify the luminous environment. There is a lack of direct relationship between light on surfaces and the vision of human eyes, which covers not only targets and surfaces but also immediate and far backgrounds. Therefore, illuminance and illuminance-based metrics are, by nature, not able to directly interpret visual performance of space occupants. However, luminance, the quantity of light reflected from a surface and transmitted into a space and eventually arriving at the eyes of space users, is a direct stimulus of vision. This study explored using perceivable luminance for design and evaluation of energy efficient and sustainable luminous environments to supplement current illuminance-based design codes. The relationship between task-based illuminance, as used in the existing codes, and the luminance of the environment perceived by a simulated space user was explored through computer simulations and field measurements using HDR imaging. The goal was to incorporate the use of luminance as the primary design metric for efficient lighting design. Evaluations were conducted for a personal office absent of daylighting. Computer simulations conducted in AGI32 were assessed to determine variance of lighting layouts possible with current illuminance-based design standards. A total of twelve lighting designs (six LED, six fluorescent) were considered and evaluated. Field measurement and HDR images obtained from previous studies were evaluated to recognize luminance preferences among 30 study participants. Results from the study indicate luminance distribution is dependent on lighting layout and directly affected by the light source. Decreasing general lighting levels

and increasing task lighting levels could improve the satisfaction of space users and reduce lighting energy consumption.

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Foremost, I would like to give my sincerest thanks to my chairperson, Dr. Hongyi Cai, for all his contributions throughout my academic career. His passion for lighting has provided great influence and drive over the years. This work would not have been possible without his guidance and advice.

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

Throughout earlier stages of lighting design, visual performance was the goal of illumination. This early objective led to the creation of illuminance-based lighting design. Emphasis of the quantitative lighting design method was placed on achieving recommended illuminance levels, typically on a horizontal work-plane, and uniformity ratios deemed necessary for completion of visual tasks. Lighting design continues to favor this quantitative approach. The use of illuminance and illuminance-based metrics at the center of lighting design revolves around inaccurate and outdated interpretations of human-light interactions, as surface-based illuminance has no direct correlation to the visual perception or visual performance of space users. This disadvantage results in a gap between current illuminance-based lighting design and the actual perceived luminous environments, which could significantly differ from the intended design. As of today, illuminance remains the dominant criteria used in the process of designing lighting solutions. Luminance, which is a direct stimulus of vision as it is directly related to perceived brightness, has only a supplemental role, if not completely ignored in current lighting design practices.

Necessary is a switch from designing lighting solutions based on the amount of light reaching horizontal work-planes, to designing for light arriving at the human eye. The goal of this switch is to create a lighting design method which couples the importance of adequate lighting for visual tasks with the need to optimize the lit environment based on the amount of light arriving to the eyes of space users. Switching to a perception-based lighting design method requires a change in understanding of how light can be effectively distributed within a space as well as a greater understanding of surface reflections. Greater understanding of interactions between humans and light could result in improved satisfaction of luminous environments and overall energy savings.

Different types of light sources and their impact on lighting design and installations must first be discussed. There has been continuous development of light sources since the invention of artificial electric light. In 1879, Thomas Edison revolutionized electric lighting with his contributions to the creation of the first electric light source, the incandescent lamp. The 20th century welcomed the invention of discharge lamps, as well as fluorescent lamps. The low cost and high light output make linear fluorescent lamps a top contender among light source options for office buildings. A study published in 2012 found that linear fluorescent lamps account for 76.5% of the total light sources in commercial buildings (Albu, Halonen, Pop, & Beu, 2013). Similar results were found in study published by Zumtobel (2014), a leading LED lighting manufacturer, which explored the perceived lighting quality of office environments according to space users. The full breakdown of light sources used in office buildings found in their study is illustrated in Figure 1.

The light source with the second highest usage in office spaces, per the Zumtobel study (2014), was the light-emitting diode (LED). LEDs have gained immense popularity since their introduction into society in the 1960s. Their lifespan and energy efficient nature give them advantage over other light sources. The Pike Research Institute predicted that by the year 2020, the use of LEDs in commercial, industrial, and outdoor stationary sectors will increase to 46% (Albu et al., 2013). Focus in this study was placed on LED and fluorescent light sources as these were found to be the most common in office buildings.

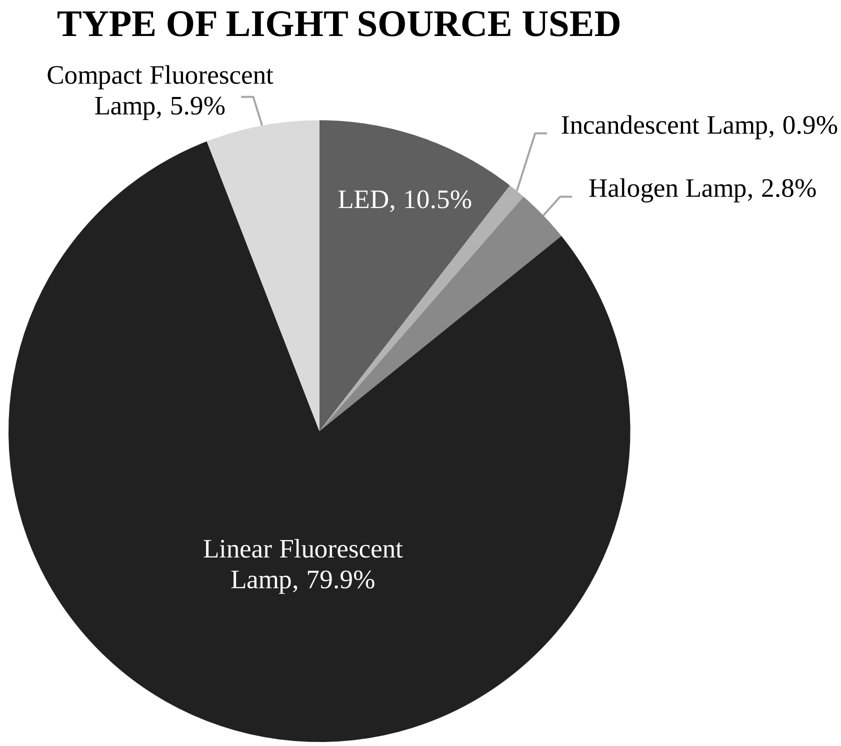


Figure 1: Light sources used in office buildings (Zumtobel, 2014)

1.1.1 ILLUMINANCE

Past and present lighting design techniques are heavily based on illuminance and other illuminance-based metrics. Illuminance, E, is the quantity of light which falls onto an object or surface (IES, 2011). Factors contributing to illuminance levels include light source optics and distance. The Illuminating Engineering Society (IES), the Commission Internationale de I'Éclairage (CIE), and the U.S. General Services Administration (GSA) all have published recommendation averages for target footcandles (fc) or lux (lx) values (Egan & Olgyay, 2002). Typically, the surface of measurement for illuminance is the horizontal work-plane. Illuminance values across vertical work-planes often get overlooked in lighting design unless significant tasks are expected to occur in the vertical orientation. Selection of recommended illuminance levels are primarily made based on occupant's age and tasks to be performed. For an office setting, illuminance values between 300 lx and 500 lx are typically recommended (Albu et al., 2013). Furthermore, uniformity ratios recommended by lighting standards are based on illuminance values. The closer illuminance levels are across the measure plane, the better the uniformity. While illuminance is not actually an affecting factor of visual performance of human eyes, it continues to be used as a primary metric amongst lighting design.

1.1.2 LUMINANCE

Luminance, L, is the quantity of light reflected from an object or surface and transmitted into the environment. Luminance is a function of illuminance and surface reflectance and directly relates to vision. Thus, it serves as a factor in many measurements of performance and perception. Current code does not include recommended values for luminance; however, luminance ratio suggestions are provided. Luminance ratios provide visual difference between objects and background. Luminance contrast between the object of focus and the immediate surrounding environment increases visual performance.

Several factors contribute to the overall luminance levels including task luminance, background luminance, and light source luminance, patterns, and gradients (IES, 2011). Special consideration must be given to luminance in work settings and areas with video terminal display (VDT) screens. Too high of luminance levels will negatively affect VDT screen task visibility (IES, 2011). Room surface reflectance values greatly contribute to the overall luminance of a space. Matte surfaces of high reflectance result in an increase of luminance as more light is reflected into the lit environment.

1.1.2.1 REFLECTANCE

Reflectance, ρ, is defined as the percentage of incident light reradiated from a surface. The remainder of the incident light is either absorbed, transmitted, or a combination of the two. There are two components of reflectance. The first being the reflectance value, namely the percentage of light that is reflected from a surface. The second component of reflectance refers to how specular, shiny, or diffuse, matte, the surface of interest is (IES, 2008). High levels of reflectance can improve the lighting efficiency and brightness of a space by creating an increased amount of inter-reflections. Adaptation when switching between tasks is greatly influenced by surface reflectance. Additionally, surfaces with higher reflectance values can positively effect energy efficiency.

1.1.3 BRIGHTNESS

Brightness is directly related to luminance as brightness is the visual response to perceive luminance, which occurs in the human brain (Cuttle, 2008). Therefore, brightness is the subjective perception of the reflected light and cannot be quantifiably measured. Research indicates luminance is the primary influence of brightness perceptions. Other factors which influence brightness include size, gradient, surround luminance, adaption, and spectral compositions. A simplified approximation of the relationship between brightness and luminance follows the 1/3 power law: in which a doubling in brightness requires an eight-fold increase in luminance (IES, 2011). The perceived brightness of a space can be increased by increasing the room surface luminance. Matte materials of high reflectance and luminaires which graze walls and ceilings can contribute to increased space brightness.

1.2 ENERGY EFFICIENCY

At an early stage of lighting design, it was believed that overhead luminaires produced light only in the downward direction. Resulting in recommended levels in lighting design generally exceeding the lighting levels necessary to complete visual task. Even after it was realized that luminaires produce light in multiple directions, values for completion of visual tasks remained higher than necessary. Over-lighting a space can result in unnecessarily high energy usage. By creating a perception-based lighting design, lighting can be better tailored towards the needs of space occupants, therefore reducing energy consumed.

According to electrical energy consumption data analyzed by the U.S. Energy Information Administration, in 2017, 10.6% of the total energy consumed by the commercial sector was consumed by lighting (U.S. Energy Information Administration [EIA], 2018). A complete breakdown of the energy consumption for the U.S. commercial sector in 2017 is depicted in Figure 2. Note that “all other uses” in Figure 2 refers to the numerous, mostly small, electrical appliances used in commercial buildings (EIA, 2018). Switching to more energy efficient light sources, providing personalized lighting control, and utilizing daylight control where applicable can all result in lower energy consumption.

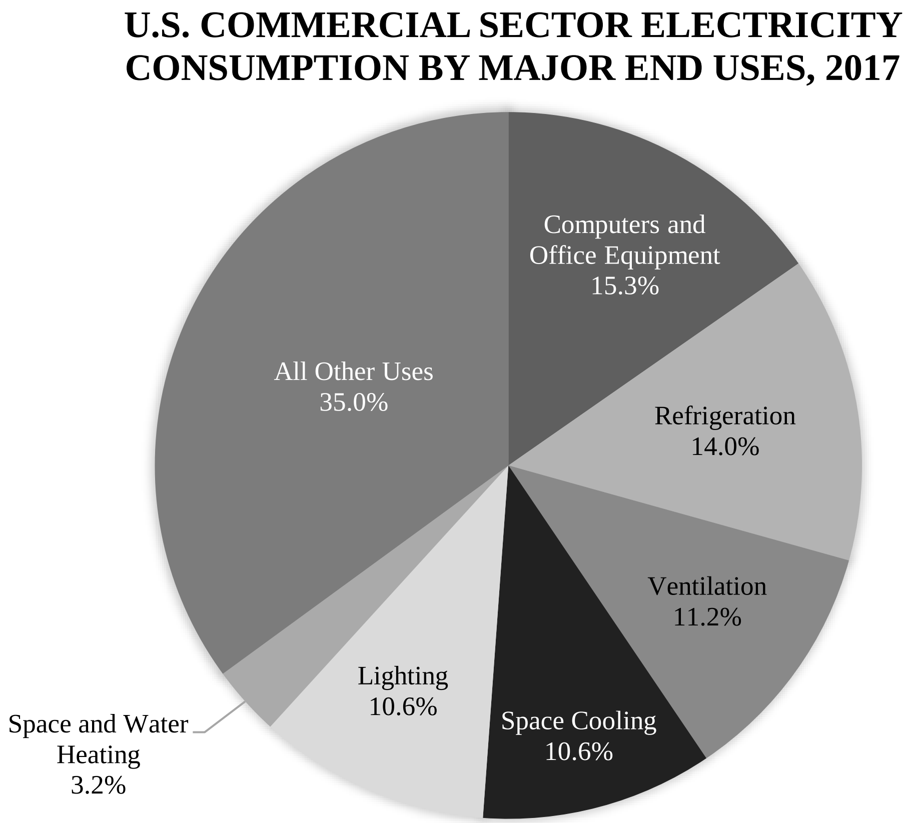


Figure 2: 2017 U.S. commercial electricity usage (EIA, 2018)

1.3 RESEARCH GOAL AND OBJECTIVES

The goal of this research was to develop and validate an alternative lighting design method to better adhere to the visual needs of space occupants for completion of tasks and overall satisfaction of the lit environment. Computer simulations and camera-aided HDR imaging technologies were utilized as aiding tools in the realization of the research goal. All design and results of this study are based on a personal office absent of daylight. Nevertheless, it is believed that similar results could occur in building types of similar conditions.

Essential to this research is the understanding that measured luminance is related to, but different from perceived brightness. Subjective analysis of brightness is dependent upon individual preferences, conditions, and visual performance, so an accurate relationship cannot be drawn between measured luminance and subjective brightness. Therefore, this research focused on the employment of physical luminance for evaluating perception-based lighting design within an objective frame.

The following research aims were established to accomplish the goal of the study:

- Evaluate limitations of current illuminance-based quantitative design standards by exploring resulting lighting effects of various lighting layouts
- Analyze the effects various lighting layouts have on luminance distribution across a space
- Evaluate the luminance patterns and luminance preferences for 30 young participants with normal visual acuity when given various levels of control over dimming for an individual office lighting environment
- Examine the energy consumption of lighting fixtures in relation to the luminance preferences of 30 participants

LED and fluorescent light sources were the only two light sources evaluated in this study. These two light sources were selected for analysis due to their popularity in commercial buildings.

CHAPTER 2 LITERATURE REVIEW

2.1 CURRENT LIGHTING DESIGN STANDARDS

Current lighting design standards and practices should first be analyzed to understand the limitations linked to existing methods. Some of the most notable and widely-used lighting design standards across North America are cited from *The Lighting Handbook,* published by the Illuminating Engineering Society. At the time of writing, the current version of *The Lighting Handbook* is the Tenth Edition, which serves as a guide and a source of knowledge for lighting professionals.

The Lighting Handbook is divided into three sections, the last of which is the *Applications* section. Focus of the *Applications* section is placed on establishing design context for various lighting applications, providing illuminance recommendations, and identifying analytical goals of lighting design using science and technology (IES, 2011). Illuminance and uniformity recommendations for numerous specified applications requiring adequate lighting systems to complete tasks and functions are listed in the *Applications* section in tables. These recommended illuminance values were determined from a system which utilizes closely spaced increments of illuminance that are assigned to tasks (IES, 2011). Both horizontal and vertical illuminance criteria, along with uniformity ratios, are listed for a multitude of applications and visual tasks in the chapters of the *Applications* section. A sample of recommendations for recommended average illuminance values for performing reading and writing tasks in an office facility is depicted in Table 1. Achieving the recommended illuminance and uniformity targets listed in the handbook often produce the belief that a satisfactory lighting design has been created. However, as previously mentioned, basing lighting levels simply off illuminance and illuminance-based metrics are not representative of true human-light interaction.

Earlier versions of the IES *Lighting Handbook* also used illuminance as the primary lighting design metric when designing for specific applications or visual tasks. The ninth edition of *The Lighting Handbook* proposed recommended illuminances which are based on the judgement of best practice for typical applications (IES, 2000). Proposed illuminance values were intended to result in high levels of visual performance. An increase of illuminance values does not guarantee greater visual performance although many designers adopted the IES system of recommended illuminance values as the primary standard for effective lighting design (IES, 2008). Table 2 conveys the determination of illuminance levels as outlined in the ninth edition of *The Lighting Handbook*.

Luminance is stated to be one of the most important quantities in lighting design (IES, 2011) but the existing standards regarding luminance are limited to primarily luminance ratio recommendations. To achieve prominence between an object and the near background, a luminance ratio of 3:1 or less, object to background, is recommended. Luminance ratios of 3:1 are typically applicable in areas of greater concentration or where safety is concerned. Luminance ratios of 10:1 are recommended to achieve distinction between an object and the far background. For situations where these aspects are not as crucial, luminance ratios of 40:1 or greater are recommended (IES, 2011). Table 3 details recommended luminance ratios to maintain task attention, visual comfort, and veiling reflections.

The ninth edition of *The Lighting Handbook* recommended an average wall luminance between 30 cd/m^2 and 100 cd/m^2 for a typical office space given illuminance across the horizontal work-plane was between 300 lx (30 fc) and 1000 lx (100 fc) (IES, 2000). This recommendation is limited as it bases recommended luminance levels solely off illuminance levels. Several more factors should be considered before this assertion can be supported.

The IES has previously proposed some typical reflectance recommendations for educational and office settings. These recommended surface and finish reflectances are outlined in Table 4. The recommended values are applicable for both matte and diffuse surfaces.

Table 1: Recommended illuminance values for office facilities (IES, 2011)

				Horizontal E_h Targets (Avg)			Vertical E_v Targets (Avg)		
				<25	**25-65**	**>65**	**<25**	**25-65**	**>65**
Office Facilities Illuminance Recommendations	**Reading & Writing – VTD Screen & Keyboard**	**CSA/ISO Types I & II**	Positive Polarity: Eh @ 2'6" AFF; Ev @ 3'6" AFF	150	300	600	75	150	300
			Negative Polarity: Eh @ 2'6" AFF; Ev @ 3'6" AFF	75	150	300	25	50	100
		CSA/ISO Types III	Positive Polarity: Eh @ 2'6" AFF; Ev @ 3'6" AFF	75	150	300	25	50	100
			Negative Polarity: Eh @ 2'6" AFF; Ev @ 3'6" AFF	37.5	75	150	15	30	60
	Reading & Writing – Handwritten Work	**Graphite/HB**	Eh @ 2'6" AFF; Ev @ 4' AFF	150	300	600	37.5	75	150
		Ballpoint/ Rollerpoint/ Felt-tip	Eh @ 2'6" AFF; Ev @ 4' AFF	150	300	600	37.5	75	150

Table 2: Determination of illuminance categories (IES, 2000)

Orientation and simple visual tasks. Visual performance is largely unimportant. There tasks are found in public spaces where reading and visual inspection are only occasionally performed. Higher levels are recommended for tasks where visual performance is occasionally important.		
A	Public spaces	30 lx (3 fc)
B	Simple orientation for short visits	50 lx (5 fc)
C	Working spaces where simple visual tasks	100 lx (10 fc)
Common visual tasks. Visual performance is important. There tasks are found in commercial, industrial, and residential applications. Recommended illuminance levels differ because of the characteristics of the visual task being illuminated. Higher levels are recommended for visual tasks with critical elements of low contrast or small size.		
D	Performing of visual tasks of high contrast and large size	300 lx (30 fc)
E	Performance of visual tasks of high contrast and small size, or visual tasks of low contrast and large size	500 lx (50 fc)
F	Performance of visual tasks of low contrast and small size	1000 lx (100 fc)
Special visual tasks. Visual performance is of critical importance. These tasks are very specialized, including those with very small or very low contrast critical elements. Recommended illuminance levels should be achieved with supplementary task lighting. Higher recommended levels are often achieved by moving the light source closer to the tank.		
G	Performance of visual tasks near threshold	3000 to 10,000 lx (300 to 1,000 fc)

Table 3: Default luminance ratio recommendations (IES, 2011)

Intent	Areas of Interest	Maximum Luminance Ratio
Maintain task attention	**Paper task to VDT screen**	
	Paper to negative-polarity VDT screen	3:1
	Paper to positive-polarity VDT screen	1:3
	Task to immediate background surfaces	3:1
	Task to distant background	
	Task to dimmer distant background	10:1
	Task to brighter distant background	1:10
Maintain visual comfort	**Task to light source**	
	Task to daylight media	1:40
	Task to luminaires	1:40
	Light-source-adjacent-surfaces to light source	
	Daylight-media-adjacent-surfaces to daylight media	1:20
	Luminaire-adjacent-surfaces to luminaires	1:20
Minimize veiling reflections	**All CSA/ISO III monitors**	
	CSA/ISO I and II negative polarity monitors in critical/high situations	
	brighter ceiling and/or wall zone to dimmer ceiling and/or wall zone	4:1
	All CSA/ISO I and II positive polarity monitors	
	CSA/ISO I and II negative polarity monitors in normal/secondary situations	
	brighter ceiling and/or wall zone to dimmer ceiling and/or wall zone	8:1

Table 4: Recommended Reflectances for Classroom and Offices (Egan & Olgyay, 2002)

	Reflectance (%)	
Surface	**Classroom**	**Office**
Ceilings	70-90	> 80
Walls	40-60	50-70
Partitions	--	40-70
Floors	30-50	20-40
Furniture and Machines	--	25-45
Desktops and Bench Tops	35-50	35-50

2.2 PREVIOUSLY PROPOSED LIGHTING DESIGN METHODS

Previous acknowledgment for alternative lighting design criteria has emerged from several sources. In the mid-twentieth century, Richard Kelly developed a method of qualitative lighting design after becoming inspired by stage lighting and perceptual psychology (Ganslandt & Hoffmann, 1992). His method consisted of three forms of light: ambient lighting, focal glow, and play of brilliance. Ambient light serves as the foundation for the other forms of light by providing general illumination to ensure the objects and people within a space are visible. The second form of light, focal glow, thrives on the knowledge that humans tend to be drawn to the most brightly lit areas within a space. An orderly flow of information would be created by providing higher levels of accent lighting to highlight essential information. Lastly, play of brilliance suggests that light itself can represent information through the creation of illumination effects. Kelly aimed to merge necessary perceptual requirements with architectural lighting.

In 1977, William M. C. Lam (1992) published a book which addressed the need for qualitative lighting design. Lam proposed activity needs and biological informational needs should be at the forefront of lighting design. Activity needs can be defined as the informational needs required to perform conscious activities. The visual-performance of the environment but be adequate enough to relay these activity needs. Biological informational needs refer to involuntary attention brought on by instinctual stimulus. Humans naturally have the desire to orientate themselves into an environment to satisfy their biological informational needs. Lam proposed that lighting to satisfy these two needs results in an efficient and successful luminous environment. Resultingly, the architecture would be complemented once lighting for activities and biological needs had occurred.

In a 1992 publication, Rüdiger Ganslandt and Harald Hoffman (1992) explored the development of a luminance-based lighting design method to better meet the needs of the architecture and the occupants utilizing the space. The proposal emphasized the employment of luminance contrast in a space by developing varying luminance levels across a visual environment. Zones would be created to accommodate corresponding zone activities. The brightest zones would be created to highlight visual tasks while surrounding spaces would be dimmer, but remain in a definable contrast range, to distinguish importance.

Studies written by Christopher Cuttle acknowledge the shortcomings of visibility-based lighting design by calling for new, measurable lighting design criteria which would relate to the visual experience of lit surroundings (Cuttle, 2010; Cuttle 2013). The assertion was made that lighting design is stuck in an archaic method invented in the nineteenth century, soon after the invention of the incandescent lamp. The basis of lighting standards became the average illuminance on horizontal work-planes and uniformity ratios. Later attempts were made to relate illuminance levels to the needs of users, but attempts were unsuccessful in prescribing their intend results. Lighting design remained centered on illuminance and uniformity targets. Cuttle asserted that lighting design must make a shift from designing to the amount of light reaching a horizontal work-plane to designing for how illuminated a space appears.

Cuttle proposed two criteria for lighting design – perceived adequacy of illumination and illumination hierarchy. Perceived adequacy of illumination relates to the level of illumination viewed as just sufficient for a space’s intended function. Mean room surface exitance (MSRE), measuring the overall density of reflected light in a space, would be used to quantify perceived adequacy of illumination. Illumination hierarchy refers to conveying the visual significance of a space’s activities or contents by creating distributions of illuminance and would be in terms of target/ambient illuminance ratio. A required change in understanding of how light is distributed for visual effectiveness and energy efficiency would need to occur for this method to come to fruition.

2.2.1 RESEARCH GAPS

A total of four research gaps were found in the investigation of a supplemental lighting design method, as follows:

1. Based on literature review, the alternative lighting-design methods by Kelly, Ganslandt, and Hoffman (Ganslandt & Hoffmann, 1992) have been insufficient in addressing the limitations associated with illuminance and illuminance-based metrics as the dominant criteria of lighting design. Illuminance is successful when it comes to addressing surface light levels but lacks in vision based human-light interactions when it comes to evaluating real-time variations of luminous environments. Therefore, illuminance-based metrics cannot be used to interpret visual information on the actual environment appearance, layout, traffic routes, or occupancy which are critical for human-light interactions. It then becomes necessary for an alternative lighting-design method to utilize a metric which better represents the light available for human perception.
2. Existing codes and standards heavily revolve around illuminance and illuminance-based metrics. Limited contents in current codes and standards are present for metrics which evaluate human perception of light in a lit environment. Research is still missing which investigates if luminance can be standardized into lighting codes and recommendations.

3. Previous studies have acknowledged the need for more visually representative design methods, but proposed solutions continue to focus on illuminance-based metrics (Cuttle, 2010; Cuttle, 2013). Proposed supplemental lighting design-methods should be based on metrics which consider visual perception and human-light interactions in a real lit environment. Cuttle (2013) attempted to bridge the gap between illuminance/room exitance and visual perception by using MRSE. Limitations of the proposed metric result in an unclear and tedious process for measuring MRSE by lighting designers. Proposed exitance metrics are difficult to interpret and calculate due to the multitude of factors within a space. Additionally, MSRE is still an illuminance-based metric. To develop a supplemental perception-based lighting design method, it is necessary to analyze a metric, luminance, which better relays human-light interactions.
4. Lastly, research indicates the intention of lighting design remains heavily focused on lighting for visibility of space users and emphasis of surrounding architecture. While lighting for these criteria is important, it is also important to account for the visual comfort of space users. Typical lighting design tends to normalize the design for different age groups of space users and intended tasks to be performed. Regard for the preferences of space users is often overlooked. Ideally, lighting design shall cater to space users' preferences to optimize occupant comfort and efficiency.

To bridge the gaps presented, the focus of this investigation was placed on employing luminance as the supplemental metric for assessing the lighting patterns and preferences of participants to achieve visual comfort. LED and fluorescent lighting systems were studied throughout this investigation. In addition to a preset lighting environment as control, occupants were offered continuous dimming control over the lighting in the space to align with each participant’s lighting preferences.

Future lighting design should provide space users with a human-light interactive lighting system which is beneficial to their individual needs and health. This research is intended to find a new luminance-based method of lighting design, which caters to space users, to supplement the existing illuminance-based design.

CHAPTER 3 – METHODOLOGY

Exploration of research can be broken down into two stages. Stage 1 relates to exploring the illuminance and luminance effects of different lighting layouts by means of computer simulations. Current illuminance-based design codes are utilized in the investigation of this stage. Stage 2 examines luminance patterns and preferences of 30 participants from a previous study (Li, 2013). Luminance values and HDR images used for analysis for Stage 2 were obtained from previous studies (Li, 2013; Poling, 2018).

3.1 STAGE 1 - COMPUTER SIMULATED DESIGN

Computer simulated lighting design was conducted to explore the variability that is present in current illuminance-based lighting design standards. A total of 12 arbitrary lighting design layouts were designed and evaluated using AGI32. A windowless, personal office (2135A) located in Learned Hall at the University of Kansas campus was used as the base model for all 12 lighting layout designs. Model dimensions measured 9'-6" wide, 12' deep, and 9'-5" high. Dimensions for this model were taken from a previous experiment conducted by Li (2013) which explored the effects of various lighting conditions on office ergonomics. Also included in the model was an office desk, measuring 60" by 30", located directly south of the door as illustrated in Figure 3. The six measurement points in the model will be discussed later in section 3.1.3. Figure 4 illustrates a 3D rendering of the modeled space with the south wall removed.

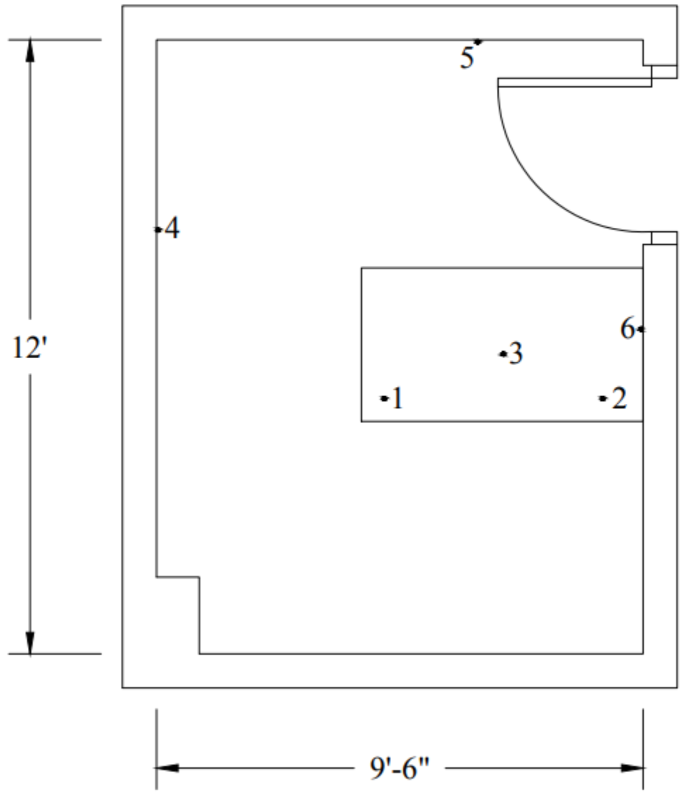


Figure 3: Plan view of model room with control points

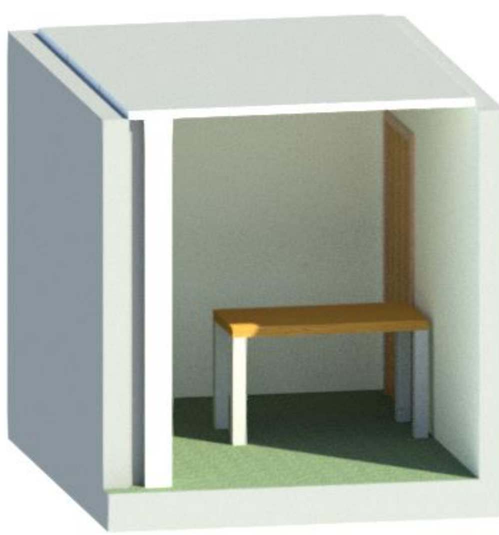


Figure 4: 3D rendering of model room

3.1.1 SURFACE REFLECTANCE

As mentioned in Chapter 1, reflectance is the percentage of incident light that is reflected from a surface. As luminance is dependent on reflectance, surface reflectance had to be calculated for major surfaces within the modeled room. Exact conditions of the modeled room could not be reproduced, as the surface conditions of the model room had changed from when original testing was conducted in the space. Figure 5 illustrates the original surface materials of the model room. Based on Figure 5, wall surfaces appeared to have remained the same. The north wall was drywall coated with an off-white paint. The white board had been removed from the room, but effects of the whiteboard were not deemed necessary for computer simulations. The east wall had similar surface conditions to the north wall but also featured a wooden door. The south wall was unpainted brick while the west wall was white-painted cinder block. Similar surfaces were located and measured to substitute for surfaces which had been altered. It was assumed that any differences possible between the initial surface reflectance the measured surface reflectance of a similar surface were very small, therefore negligible. The original flooring had been replaced with carpet, so the surface reflectance of the floor was measured in another office in Learned Hall (2134C) where green tile was present. The 2' x 4' ceiling tiles could not be reached for accurate measurement, so the surface reflectance of ceiling tiles, similar in texture and appearance, was found via the internet and used in substitution. The desk, document holder, and VDT display had all been removed from the model room. Measurements for these surfaces were performed in their new locations.

Figure 5: Fisheye view of testing room (Li, 2013)

Reflectance measurements were completed using a Minolta Illuminance Meter T 10M, shown in Figure 6. The lux meter was held at approximately one inch away from each surface being measured. At each measurement point, the lux meter was first positioned with the sensor facing away from the surface to measure the amount of light reaching the specified point. The sensor was then flipped to face the surface of the measurement point to measure the amount of light being reflected by the surface. These values were then inserted into Equation (1) to calculate the reflectance of each surface.

$$\rho = \frac{\text{amount of reflected light}}{\text{total light coming to surface}} \tag{1}$$

The measurement process was completed at least three times for each surface for increased accuracy. The computed reflectance results for each surface measurement were then averaged together to achieve one reflectance value for each measured surface. Table 5 outlines the averaged measured reflectances for each surface. The averaged reflectance measurements were then inputted into all AGI32 models and used for computer simulation calculations. Reflectances were assumed constant and were unchanged amongst lighting layouts.

Figure 6: Minolta Illuminance Meter T 10M

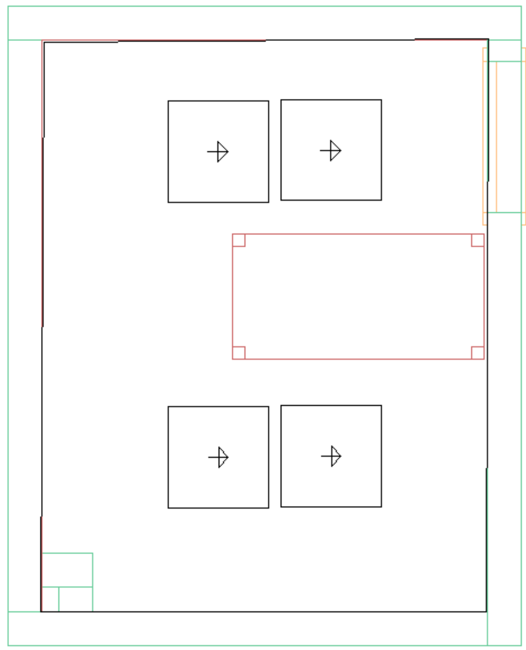
Table 5: Surface reflectance values

Surface Measured	ρ_{avg}
North Wall	0.82
East Wall	0.67
South Wall	0.27
West Wall	0.73
Chase	0.74
Door	0.41
Floor	0.18
Ceiling	0.83
Desk	0.12
Computer Screen	0.18
Document Holder	0.38

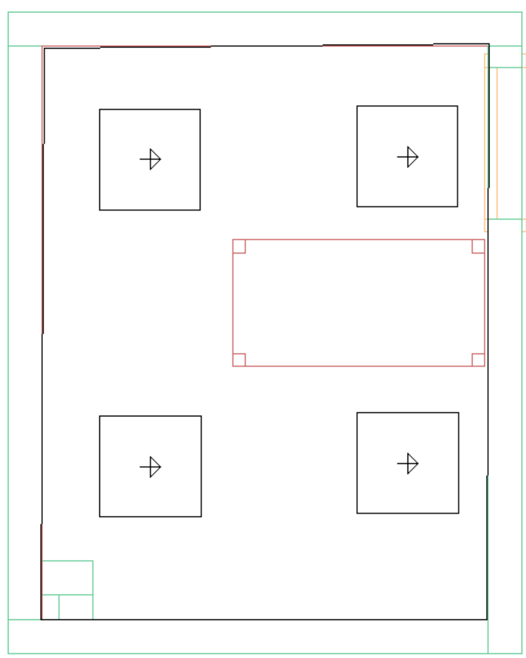
3.1.2 LIGHTING LAYOUTS

Twelve arbitrary lighting layouts were created using AGI32. Six lighting layouts were composed using Cree 2’ x 2’ recessed architectural LED troffers. A grid system was not used when designing layouts, so luminaires could be placed at any point on the ceiling within the room boundaries. Each of the six lighting layouts consist of four luminaires to maintain a consistent overall lumens output for accurate analysis. Six lighting layouts, identical to the LED lighting layouts, were created using Philips 2’ x 2’ recessed architectural fluorescent troffers. Fluorescent fixtures were fitted with linear fluorescent T8 lamps. Illustrated in Figure 7 are the six lighting arrangements that were used for computer simulations.

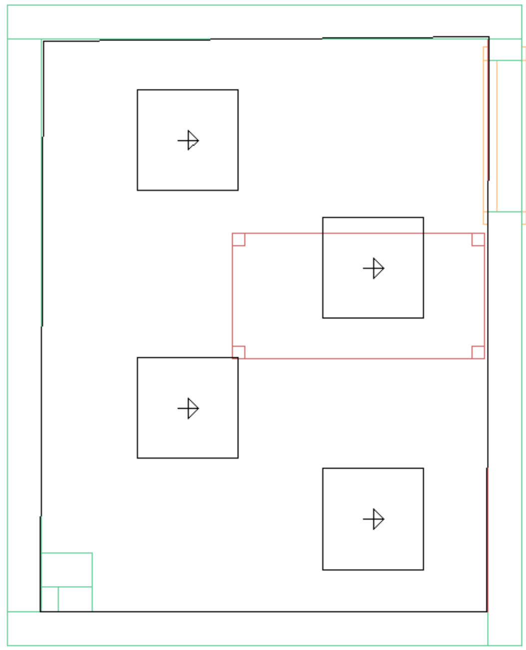
Through continuous dimming, the photometric performance of the LED Cree troffer can reach similar levels to the photometric performance of the Philips Fluorescent troffer. For this reason, accurate comparisons can be made between the LED lighting layouts and the fluorescent lighting layouts.



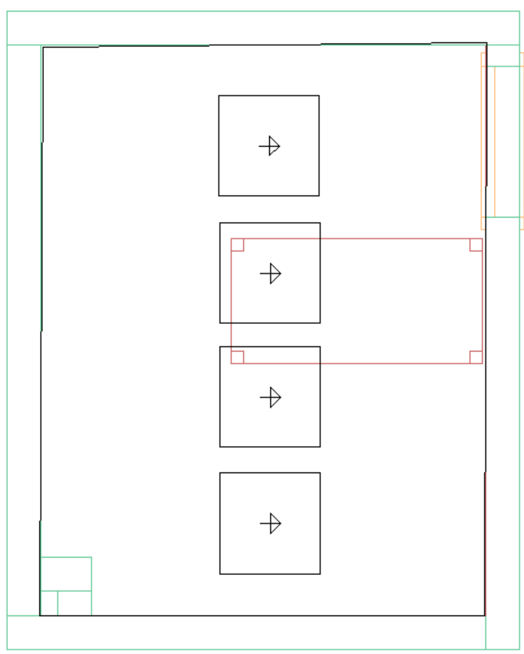
(a)



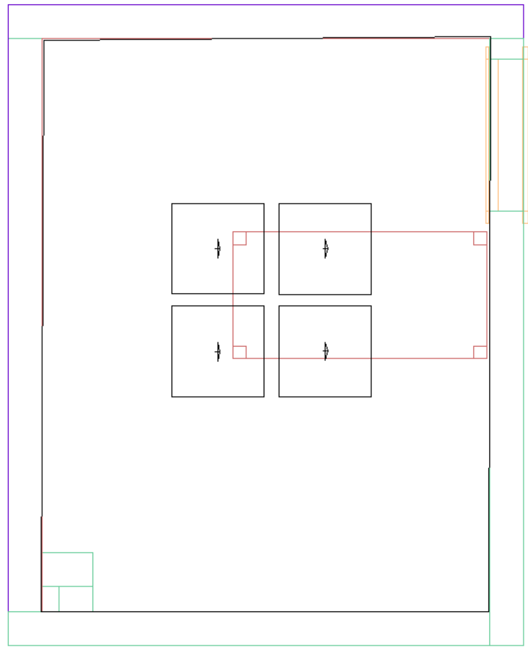
(b)



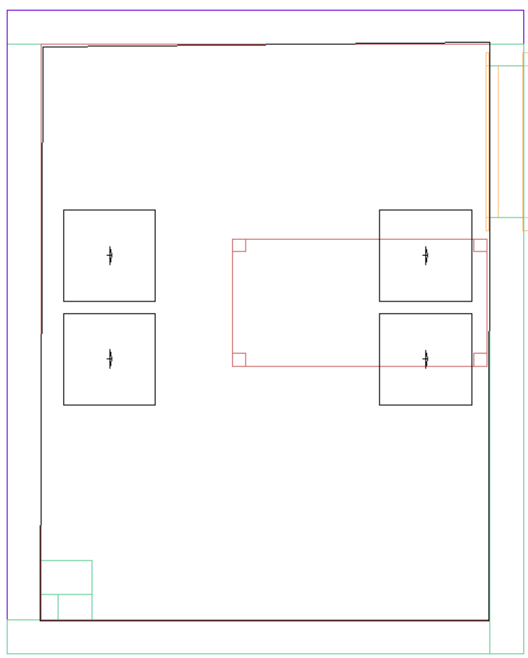
(c)



(d)



(e)



(f)

Figure 7: AGI32 lighting arrangements. (a) Lighting Arrangement 1, (b) Lighting Arrangement 2, (c) Lighting Arrangement 3, (d) Lighting Arrangement 4, (e) Lighting Arrangement 5, (f) Lighting Arrangement 6

3.1.3 ILLUMINANCE DATA

To realize the goal of Stage 1, similar illuminance values across designated surfaces must be achieved for all six lighting layouts. A total of six control points were selected at various locations in the model to depict illuminance values across the space. Figure 3 details the locations of the control points. Control points 1, 2, and 3 were located horizontally on the desktop. Control points 4, 5, and 6 were vertical points located along the west, north, and east wall respectively. Control points 4, 5, and 6 were all placed at 4 ft above the finished floor. For each layout, the lighting system was dimmed as necessary for the six control points to reach an average target illuminance of 30 fc (300 lx). A value of 30 fc is within the range suggested by the IES *Lighting Handbook*, 10th edition, for Reading and Writing VDT Screen and Keyboard tasks in an office facility.

Illuminance values were then calculated in AGI32 along the following surfaces - north wall, east wall, west wall, south wall, floor, and desktop. The ceiling was omitted from measurement as error occurred during AGI32 calculation from inconsistencies between LED and fluorescent IES files. Measurement points were placed in a 2’ x 2’ grid for all aforementioned surfaces. Points which were located behind or within objects were removed to avoid calculation error.

3.1.4 LUMINANCE CALCULATION

For all 12 lighting layouts, illuminance values were used along with surface reflectance values to calculate the luminance of each measurement point. Additionally, the average luminance across each measured surface was calculated. Calculated reflectance values were used in luminance calculation. Equation 2 was used to calculate luminance values for all designed lighting layouts. This equation truly applies to cases of completely diffuse reflection. However, results stemming from the use of Equation 2 are acceptable approximations for practice.

$$L = \frac{E \times \rho}{\pi} \tag{2}$$

Where:

L = luminance (cd/m^2)

E = illumination level or illuminance (m)

ρ = reflectance (%)

Both illuminance and luminance results for Stage 1 were analyzed. Results of analysis can be found in Chapter 4.

3.2 STAGE 2 – OFFICE LIGHTING PREFERENCE ANALYSIS

3.2.1 SET-UP AND INTRODUCTION

With such large luminance variation possible from current lighting standards, the next step to bridging the design gap was to examine lighting preferences in a real lit environment. For analysis of lighting preferences, the layout of the lighting system remained constant while fixture type and lighting control varied. Analyzed data was collected in a study conducted by Li (2013) in which a total of 30 participants were given dimming control of two lighting systems, one fluorescent system and one LED system, in an office environment. The experiment was conducted in a personal, windowless office in Learned Hall at the University of Kansas campus. Both lighting systems comprised of four 2’ x 2’ recessed troffers and one task lamp. For each lighting system, participants completed tasks once in a standardized lighting condition with no control over the lighting system. The participants then repeated the tasks with access to continuous dimming control. An HDR image was taken once participants completed the designated office tasks under each lighting condition, resulting in a total of 120 HDR images.

Eight control points were selected in Li's study (2013) to gather photometric data as illustrated in Figure 9. Control points 1, 2, and 3 were horizontal measurement points located on the desktop. Point 4 was a vertical measurement point located at the center of a document holder containing a ColorChecker and a printed sheet of paper, depicted in Figure 8. Point 5 was positioned at the center of a 23" VDT display. Control points 6, 7, and 8 were vertical points located along the west, north, and east wall, respectively, at 4 ft above the finished floor. All points were denoted using small squares of white printer paper. The illuminance value at each of the eight points was measured and recorded under all four lighting conditions for each participant. Illuminance values were measured using a Minolta LS-100 Luminance hand meter.

Figure 8: Document stand with ColorChecker and printed paper (Li, 2013)

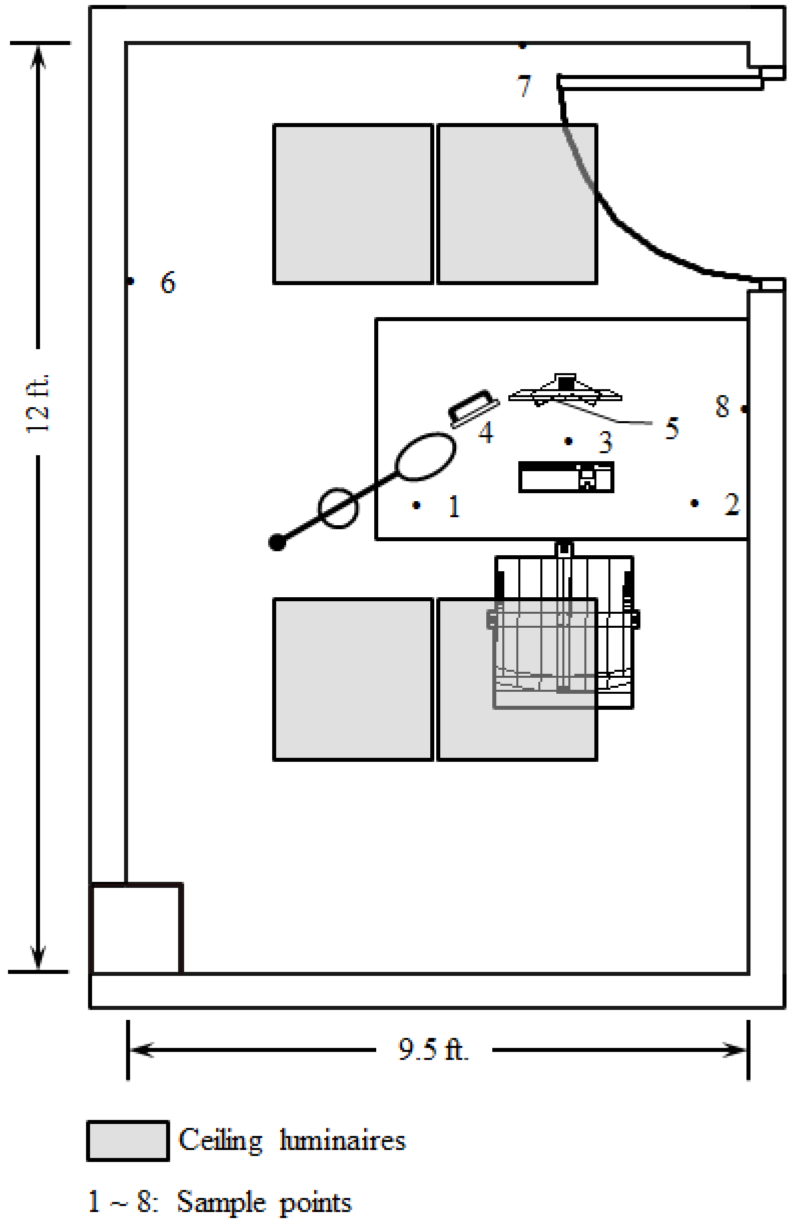


Figure 9: Plan view of test room (Li, 2013)

Participants involved in the experiment were between 18 and 29 years of age, with an average age of 21.6 years old and a standard deviation of 3.35. Out of the 30 participants, 19 were female and 11 were male. All participants possessed either 20/20 or 20/16 vision, with 21 participants having 20/20 vision and 9 participants having 20/16 vision, and normal color vision.

Lighting systems analyzed consisted of general lighting in conjunction with task lighting. General lighting was achieved using ceiling recessed 2’ x 2’ troffers. For the LED lighting system, four Cree 2’ x 2’ Architectural LED Troffers were specified. The fluorescent lighting system was composed of four 2’ x 2’ Architectural Fluorescent Troffers with T8 lamps. The study was conducted using a LED Cree fixture and a fluorescent Philips fixture which have similar light outputs. The arrangement of the general lighting is illustrated in Figure 9. Dimming for these general lighting systems was achieved with the use of a Lutron DIVA wall dimmer which features continuous dimming to 5%. In addition to the general lighting, a floor-standing task lamp was placed to the left of the desk to provide participants with increased luminance contrasts for completing the designated tasks. The task lamp light source used in the LED lighting system was the Philips Award Winning LED. A Bulbrite T3 Compact Fluorescent Lamp (CFL) bulb was employed for the fluorescent lighting system. Dimming control of task lighting consisted of a Lutron Credenza CFL/LED dimmer with continuous dimming.

General lighting was dimmed to reach an average horizontal illuminance of 40 fc (400 lx) on the desktop during experiments where lighting control was not provided for the participants. Task lighting was dimmed until the document holder and the computer screen had similar illuminance values. In experiments where dimming control was given to participants, both the general lighting system and the task lighting system dimming levels were allowed be increased or decreased to meet the participant's preferences. Point luminance values were calculated using the illuminance values that were recorded from the eight sample points.

3.3 HIGH DYNAMIC RANGE IMAGING AND ANALYSIS

Three series of low dynamic range (LDR) images were captured to record the lighting conditions for every participant at the end of each lighting system testing condition. Images were captured using a Canon T2i digital camera fitted with a Sigma standard 30mm lens and a circular 4.5mm fisheye lens. The camera was positioned at the location of the participant's eyes to mimic the view of the participant. For each series of LDR images, the camera lens and aiming position were altered. Each sequence of LDR images consisted of 18 images. HDR images were then created by combining these sequences of LDR images in Photosphere. The results from this experiment can be found in Li's thesis (2013). Relevant to this study are the HDR images composed using LDR images captured when the camera was fitted with the fisheye lens and aimed at the center of the VDT screen. A total of 120 HDR images were composed from LDR images captured using the fisheye lens and analyzed in this study. A sample HDR image captured with the fisheye lens is offered in Figure 10.

Figure 10: HDR image captured using fisheye lens (Poling, 2018)

HDR images from Li's study were further examined as part of an experiment conducted by Reid Poling (Poling, 2018) which explored a new method for calculating luminous flux. The method used for analysis of HDR images involved using only data present in the HDR images to calculate the luminous flux of image sub areas. Small changes between HDR images due to participant position and object movement were deemed negligible throughout analysis. The HDR image for Participant 1 under the fluorescent lighting system without lighting control was used as the basis for all other image analysis. This image was used as the basis for calculating solid angles and apparent angles necessary for flux calculations. For calculating apparent area, the program HDRscope was used to divide the entire HDR image area into designated subareas based on major surfaces and objects. Larger surfaces were further divided to increase calculation accuracy. Figure 11 illustrates the AutoCAD illustration used for finding the areas of major surfaces and objects. The mean luminance for each subarea used in apparent area calculations was then determined using HDRscope before the luminous flux was calculated. The mean luminance subarea values were essential to this study. Area luminance values calculated were used to analyze the luminance patterns and preferences of the 30 study participants.

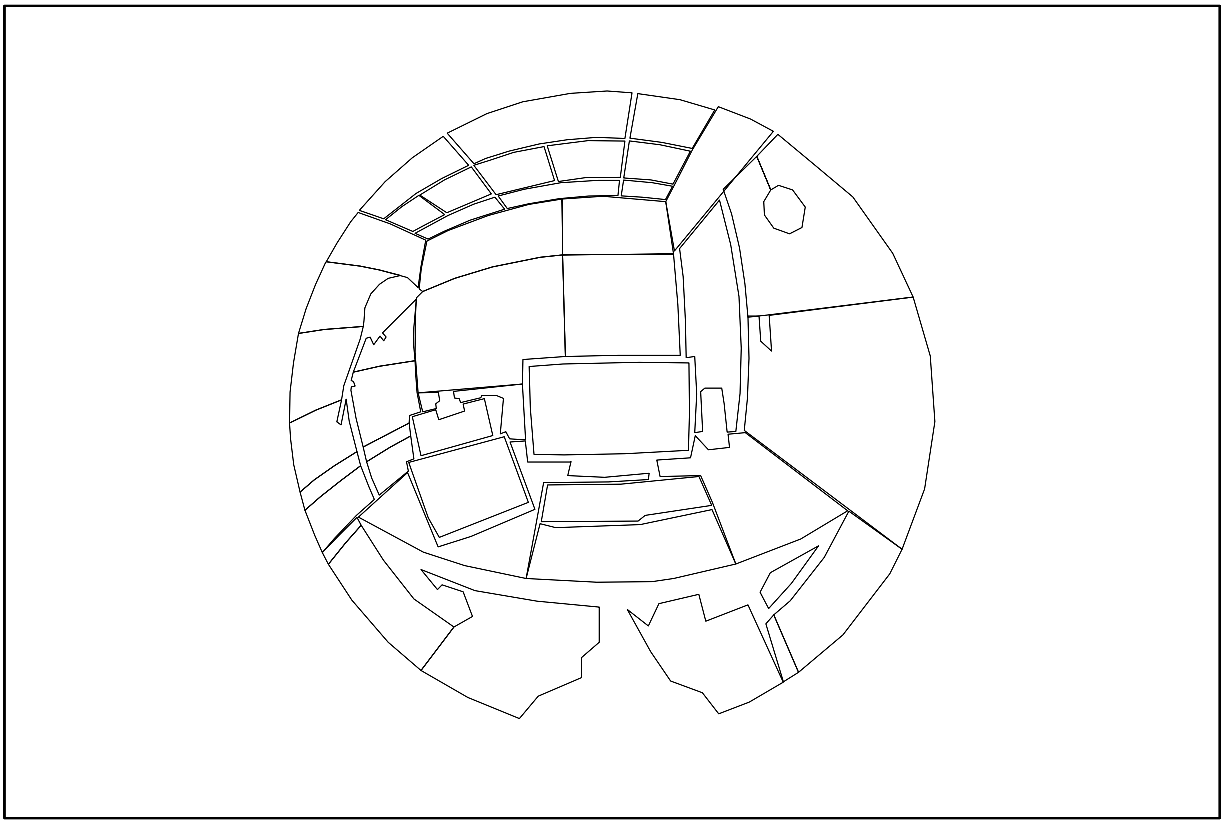
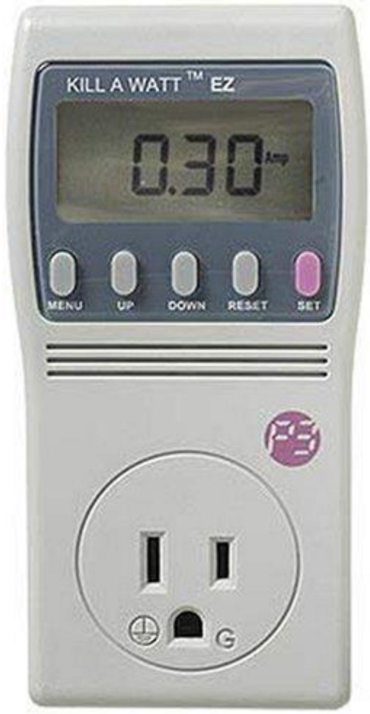


Figure 11: AutoCAD recreation of HDR image (Poling, 2018)

3.4 ENERGY DATA

Power consumption data was obtained from Li's study (2013). Energy meters were attached to the power connection for the general lighting and the task lighting. The general lighting system utilized an Efergy Elite Classic 3.0 Electricity Monitor as shown in Figure 12(a). The task lighting system was connected to a P3 international P4460 Kill A Watt EZ Electricity Usage Meter, illustrated in Figure 12(b). Power consumption was recorded three times during each of the four lighting conditions for all thirty participants. The average of the three energy recordings for each lighting system was calculated and used for additional evaluation.

(a)



(b)

Figure 12: Energy meters. (a) Efergy Elite Classic 3.0 Electricity Monitor, (b) P3 international P4460 Kill A Watt EZ Electricity Usage Monitor. (Li, 2013)

CHAPTER 4 DATA ANALYSIS AND RESULTS

4.1 INTRODUCTION

Data collected throughout this study was analyzed using IBM SPSS Software 25, a statistical analysis software. Analysis was separately performed on data gathered in Stage 1 and Stage 2 of the experiment. The goal of data analysis for Stage 1 was to assess the correlation of illuminance and luminance values that result from various lighting layouts. Data analysis was performed for Stage 2 to realize common patterns in luminance levels based on individual lighting preferences when performing tasks in an office environment.

The strength of correlation was determined by using the SPSS bivariate function to generate the Pearson product-moment correlation coefficient, typically denoted by the variable r. The Pearson correlation coefficient determines the strength of linear association between variables. Coefficient values can range from -1 to +1 depending on the strength of the relationship. The closer the Pearson correlation coefficient is to -1 or +1, the stronger the variable association. A value closer to 0 indicated little association between the compared variables. Table 6 was used as a guide for evaluating the strength of correlation between compared variables (Evans, 1996). Separate SPSS bivariate tests were run for LED lighting systems and for fluorescent lighting systems to allow for accurate conclusions to be drawn for each lighting system.

Table 6: Strength of correlation

Absolute Value of *r*	Strength of Correlation
0.00 – 0.19	Very Weak
0.20 – 0.39	Weak
0.40 – 0.59	Moderate
0.60 – 0.79	Strong
0.80 – 1.00	Very Strong

4.2 STAGE 1 ANALYSIS – COMPUTER SIMULATED DESIGN

AGI32 calculated illuminance values of all six control points, for each lighting layout, were recorded in an Excel sheet. Also recorded were the average of all sample points and the level of dimming required for control points to reach an average of approximately 30 fc for each lighting arrangement. Table 7 depicts a sample of the illuminance results for LED lighting Arrangement 1. The full Excel sheet of results for both LED and fluorescent can be found in the Appendix E. For LED arrangements, SPSS results for all six sample points plus the average of sample points conclude very strong correlation between arrangements as all correlation coefficient values are greater than 0.95. It can then be stated that illuminance values calculated in AGI32 at these six points under LED lighting are all statistically the same. Results of the sample points under fluorescent lighting conditions deduced the same results as all coefficient values were above 0.95. Thus, a very strong correlation was present between the fluorescent lighting arrangements, so it can confidently be stated that the illuminance values across the six tested lighting layouts are statistically identical. The coefficient values procured from analysis of LED arrangements and fluorescent arrangements are outlined in Table 8 and Table 9, respectively.

Table 7: LED Arrangement 1 control points illuminance, dimmed to 70%

Sample Point	Illuminance (fc)
Point 1	46.0
Point 2	34.7
Point 3	42.9
Point 4	17.8
Point 5	20.8
Point 6	18.0
AVG	**30.0**

Table 8: LED arrangements control points correlation coefficients

	A1	A2	A3	A4	A5	A6
Arrangement 1 (A1)	1.000	0.990**	0.996**	0.998**	0.999**	0.979**
Arrangement 2 (A2)	0.990**	1.000	0.996**	0.987**	0.988**	0.998**
Arrangement 3 (A3)	0.996**	0.996**	1.000	0.996**	0.996**	0.990**
Arrangement 4 (A4)	0.998**	0.987**	0.996**	1.000	1.000**	0.976**
Arrangement 5 (A5)	0.999**	0.989**	0.996**	1.000**	1.000	0.977**
Arrangement 6 (A6)	0.979**	0.998**	0.990**	0.976**	0.977**	1.000

** Correlation is significant at the 0.01 level (2-tailed)

Table 9: Fluorescent arrangements control points correlation coefficients

	A1	A2	A3	A4	A5	A6
Arrangement 1 (A1)	1.000	0.989**	0.996**	0.998**	0.999**	0.977**
Arrangement 2 (A2)	0.989**	1.000	0.996**	0.985**	0.986**	0.997**
Arrangement 3 (A3)	0.996**	0.996**	1.000	0.996**	0.996**	0.989**
Arrangement 4 (A4)	0.998**	0.985**	0.996**	1.000	1.000**	0.973**
Arrangement 5 (A5)	0.999**	0.986**	0.996**	1.000**	1.000	0.974**
Arrangement 6 (A6)	0.977**	0.997**	0.989**	0.973**	0.974**	1.000

** Correlation is significant at the 0.01 level (2-tailed)

Once it was concluded that both the LED and the fluorescent arrangements were similar in illuminance across designated measurement points, luminance values across surfaces were analyzed. AGI32 illuminance results for every calculation grid were transferred to Excel where luminance calculations were performed. For preliminary assessment, only the average luminance was analyzed. Data for average luminance was generated using the average illuminance which was calculated for all major surfaces of the twelve lighting systems. Maximum luminance and minimum luminance were also calculated using illuminance data obtained from AGI32. Table 10 conveys a sample of a major surface summary data table created in Excel for LED Arrangement 1. Statistical analysis was performed to assess the correlation of average luminance for both LED arrangements and fluorescent arrangements. Calculation results of LED arrangements, portrayed in Table 11, show there is very strong correlation between average surface luminances on major surfaces. Average surface luminance values for fluorescent arrangements show almost identical results with all correlation coefficient above 0.90 as illustrated in Table 12. Results indicate average luminance across major surfaces is statistically the same.

Table 10: Summary data for LED Arrangement 1

	Illuminance (fc)					Reflectance	Luminance (cd/m^2)		
	Average	Maximum	Minimum	Avg/Min	Max/Min		Average	Maximum	Minimum
Floor	24.17	28.80	17.50	1.38	1.65	0.18	14.59	17.39	10.57
Desk	40.70	46.10	33.50	1.21	1.38	0.12	16.73	18.95	13.77
North Wall	25.33	46.30	14.40	1.76	3.22	0.82	71.58	130.85	40.69
East Wall	21.39	34.20	10.40	2.06	3.29	0.67	49.00	78.35	23.83
South Wall	23.48	41.00	12.80	1.83	3.20	0.27	21.50	37.55	11.72
West Wall	22.36	32.60	14.40	1.55	2.26	0.73	55.91	81.51	36.00

Table 11: LED arrangements summary luminance correlation coefficients

	A1	A2	A3	A4	A5	A6
Arrangement 1 (A1)	1.000	0.988**	0.991**	0.997**	0.988**	0.933**
Arrangement 2 (A2)	0.988**	1.000	0.999**	0.993**	0.997**	0.976**
Arrangement 3 (A3)	0.991**	0.999**	1.000	0.995**	0.996**	0.970**
Arrangement 4 (A4)	0.997**	0.993**	0.995**	1.000	0.993**	0.949**
Arrangement 5 (A5)	0.988**	0.997**	0.996**	0.993**	1.000	0.974**
Arrangement 6 (A6)	0.933**	0.976**	0.970**	0.949**	0.974**	1.000

** Correlation is significant at the 0.01 level (2-tailed)

Table 12: Fluorescent arrangements summary luminance correlation coefficients

	A1	A2	A3	A4	A5	A6
Arrangement 1 (A1)	1.000	0.988**	0.992**	0.998**	0.989**	0.923**
Arrangement 2 (A2)	0.988**	1.000	0.999**	0.991**	0.997**	0.971**
Arrangement 3 (A3)	0.992**	0.999**	1.000	0.995**	0.996**	0.963**
Arrangement 4 (A4)	0.998**	0.991**	0.995**	1.000	0.993**	0.935**
Arrangement 5 (A5)	0.989**	0.997**	0.996**	0.993**	1.000	0.965**
Arrangement 6 (A6)	0.923**	0.971**	0.963**	0.935**	0.965**	1.000

** Correlation is significant at the 0.01 level (2-tailed)

Further analysis was necessary to determine if individual measurement points would produce similar statistical results. For every surface where a calculation grid was located, each individual measurement point was given an alphanumeric label – the letter corresponded to the surface being measured and the number referenced the location of the point in relation to the grid. For example, N11 refers to the point located at the first row and first column position along the north wall. Figure 13 portrays the grid system used along the north wall of all arrangements. For all twelve arrangements, illuminance values at each measurement point were transferred to Excel where the luminance values at each measurement point were then calculated. A sample of the Excel table made for the north wall is illustrated in Table 13 and Table 14.

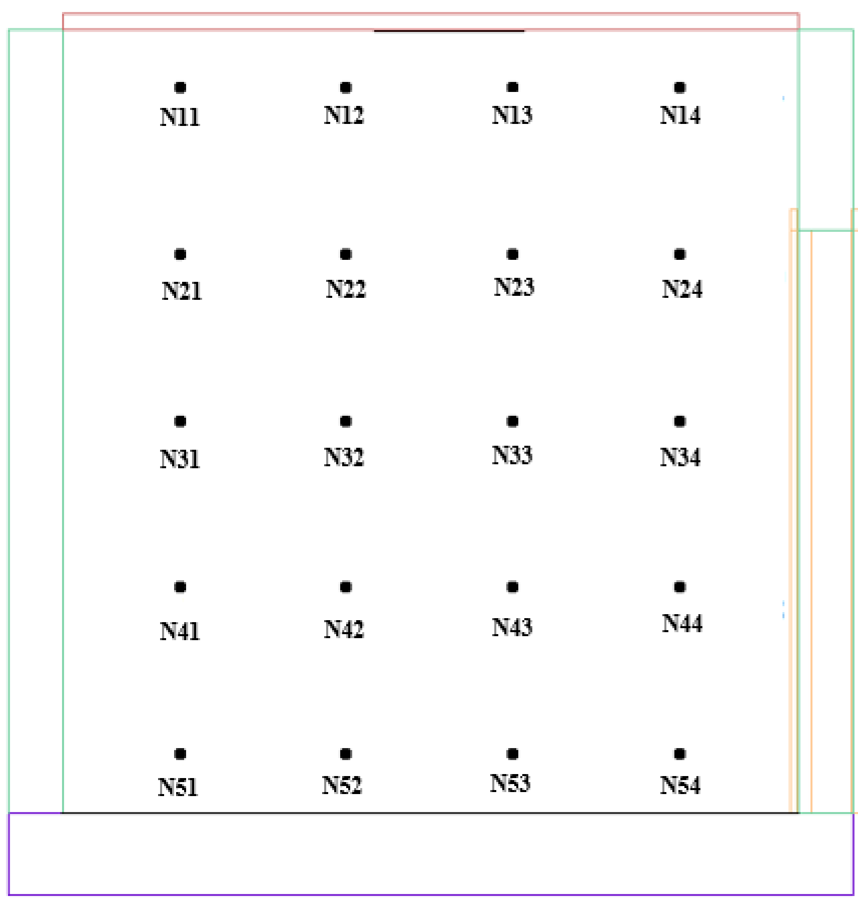


Figure 13: Calculation grid of north wall with measurement points

Table 13: Sample illuminance data sheet for LED arrangements north wall measurement points

Point	Arrangement 1	Arrangement 2	Arrangement 3	Arrangement 4	Arrangement 5	Arrangement 6
N11	17.7	32.3	20.4	10.1	10.4	13.7
N12	33.3	23.8	26.4	19.7	11.5	14.2
N13	33.2	23.2	14.5	22.7	11.3	13.9
N14	17.2	32.9	11.0	10.7	9.9	13.1
N21	31.0	41.7	32.8	21.4	22.4	27.5
N22	46.3	37.6	38.3	34.7	28.1	26.6
N23	46.0	36.7	29.2	37.2	28.1	25.9
N24	29.3	39.7	21.4	23.0	21.6	25.6
N31	25.5	27.8	25.6	21.1	23.2	25.9
N32	29.4	28.2	27.6	25.6	26.5	26.3
N33	28.7	27.4	25.7	26.0	26.2	25.5
N34	23.2	25.4	21.5	20.8	21.7	23.8
N41	20.6	21.5	20.4	17.0	19.5	21.1
N42	21.7	22.0	21.4	18.5	21.0	21.6
N43	20.9	21.2	20.5	18.2	20.4	20.8
N44	18.1	19.0	17.9	15.8	17.6	18.9
N51	16.1	16.8	15.9	12.3	15.1	16.2
N52	17.3	17.8	17.0	13.2	16.5	17.3
N53	16.6	17.1	16.4	12.9	15.9	16.8
N54	14.4	15.1	14.3	11.3	13.8	14.9

Table 14: Sample luminance data sheet for LED arrangements north wall measurement points

Point	Arrangement 1	Arrangement 2	Arrangement 3	Arrangement 4	Arrangement 5	Arrangement 6
N11	50.0	91.3	57.7	28.5	29.4	38.7
N12	94.1	67.3	74.6	55.7	32.5	40.1
N13	93.8	65.6	41.0	64.2	31.9	39.3
N14	48.6	93.0	31.1	30.2	28.0	37.0
N21	87.6	117.8	92.7	60.5	63.3	77.7
N22	130.8	106.3	108.2	98.1	79.4	75.2
N23	130.0	103.7	82.5	105.1	79.4	73.2
N24	82.8	112.2	60.5	65.0	61.0	72.3
N31	72.1	78.6	72.3	59.6	65.6	73.2
N32	83.1	79.7	78.0	72.3	74.9	74.3
N33	81.1	77.4	72.6	73.5	74.0	72.1
N34	65.6	71.8	60.8	58.8	61.3	67.3
N41	58.2	60.8	57.7	48.0	55.1	59.6
N42	61.3	62.2	60.5	52.3	59.3	61.0
N43	59.1	59.9	57.9	51.4	57.7	58.8
N44	51.2	53.7	50.6	44.7	49.7	53.4
N51	45.5	47.5	44.9	34.8	42.7	45.8
N52	48.9	50.3	48.0	37.3	46.6	48.9
N53	46.9	48.3	46.3	36.5	44.9	47.5
N54	40.7	42.7	40.4	31.9	39.0	42.1

Results from SPSS analysis comparing LED luminance values at every measurement point across each surface of all six lighting layouts are listed in Table 15. Results concluded all comparisons were statistically significant at the 0.05 level. Fluorescent luminance correlation results across all surfaces, shown in Table 16, also concluded all comparisons were statistically significant at the 0.05 level.

Table 15: LED arrangements correlation coefficients, luminance across all surfaces

	A1	A2	A3	A4	A5	A6
Arrangement 1 (A1)	1.000	0.805**	0.654**	0.973**	0.899**	0.460**
Arrangement 2 (A2)	0.805**	1.000	0.563**	0.744**	0.731**	0.507**
Arrangement 3 (A3)	0.654**	0.563**	1.000	0.661**	0.651**	0.383**
Arrangement 4 (A4)	0.973**	0.744**	0.661**	1.000	0.942**	0.461**
Arrangement 5 (A5)	0.899**	0.731**	0.651**	0.942**	1.000	0.563**
Arrangement 6 (A6)	0.460**	0.507**	0.383**	0.461**	0.563**	1.000

** Correlation is significant at the 0.01 level (2-tailed)

Table 16: Fluorescent arrangements correlation coefficients, luminance across all surfaces

	A1	A2	A3	A4	A5	A6
Arrangement 1 (A1)	1.000	0.782**	0.924**	0.971**	0.891**	0.442**
Arrangement 2 (A2)	0.782**	1.000	0.815**	0.723**	0.734**	0.534**
Arrangement 3 (A3)	0.924**	0.815**	1.000	0.919**	0.927**	0.556**
Arrangement 4 (A4)	0.971**	0.723**	0.919**	1.000	0.935**	0.445**
Arrangement 5 (A5)	0.891**	0.734**	0.927**	0.935**	1.000	0.554**
Arrangement 6 (A6)	0.442**	0.534**	0.556**	0.445**	0.554**	1.000

** Correlation is significant at the 0.01 level (2-tailed)

Data was then separated by major surface and reevaluated. Table 17 shows the results from analysis for LED arrangements. Across the north wall, correlation was statistically significant at a 0.05 level for all arrangements except for Arrangement 2 when compared to Arrangement 5. The weakest correlation coefficients across the east wall was seen for Arrangement 6 when compared to all other Arrangements. On the south wall, all arrangements were statistically significant except when compared to Arrangement 3. All comparisons which featured Arrangement 3 resulted in weak correlation. Correlation coefficients for the west wall ranged across the spectrum, from very weak to very strong. Correlation at the floor proved all arrangements were statistically significant. It is assumed that the light had diffused by the time it reached the floor resulting in significant correlation. Lastly, desktop values were compared, and results indicate very strong correlation between all arrangements. The limited number of calculation points across the desktop could influence the results.

Table 17: LED arrangements correlation coefficients, luminance separated by major surface

		A1	A2	A3	A4	A5	A6
North Wall	**Arrangement 1 (A1)**	1.000	0.651**	0.786**	0.942**	0.588**	0.556*
	Arrangement 2 (A2)	0.651**	1.000	0.629**	0.570**	0.418	0.551*
	Arrangement 3 (A3)	0.786**	0.629**	1.000	0.781**	0.750**	0.764**
	Arrangement 4 (A4)	0.942**	0.570**	0.781**	1.000	0.797**	0.734**
	Arrangement 5 (A5)	0.588**	0.418	0.750**	0.797**	1.000	0.954**
	Arrangement 6 (A6)	0.556*	0.551*	0.764**	0.734**	0.954**	1.000
		A1	**A2**	**A3**	**A4**	**A5**	**A6**
East Wall	**Arrangement 1 (A1)**	1.000	0.408*	0.815**	0.966**	0.890**	0.021
	Arrangement 2 (A2)	0.408*	1.000	0.402*	0.302	0.270	0.084
	Arrangement 3 (A3)	0.815**	0.402*	1.000	0.883**	0.839**	0.235
	Arrangement 4 (A4)	0.966**	0.302	0.883**	1.000	0.935**	0.044
	Arrangement 5 (A5)	0.890**	0.270	0.839**	0.935**	1.000	0.219
	Arrangement 6 (A6)	0.021	0.084	0.235	0.044	0.219	1.000
		A1	**A2**	**A3**	**A4**	**A5**	**A6**
South Wall	**Arrangement 1 (A1)**	1.000	0.918**	0.283	0.940**	0.814**	0.817**
	Arrangement 2 (A2)	0.918**	1.000	0.279	0.801**	0.760**	0.808**
	Arrangement 3 (A3)	0.283	0.279	1.000	0.270	0.357	0.349
	Arrangement 4 (A4)	0.940**	0.801**	0.270	1.000	0.648**	0.655**
	Arrangement 5 (A5)	0.814**	0.760**	0.357	0.648**	1.000	0.988**
	Arrangement 6 (A6)	0.817**	0.808**	0.349	0.655**	0.988**	1.000
		A1	**A2**	**A3**	**A4**	**A5**	**A6**
West Wall	**Arrangement 1 (A1)**	1.000	0.362	0.953**	0.955**	0.878**	-0.033
	Arrangement 2 (A2)	0.362	1.000	0.450*	0.190	0.133	0.160
	Arrangement 3 (A3)	0.953**	0.450*	1.000	0.908**	0.903**	0.177
	Arrangement 4 (A4)	0.955**	0.190	0.908**	1.000	0.941**	-0.013
	Arrangement 5 (A5)	0.878**	0.133	0.903**	0.941**	1.000	0.164
	Arrangement 6 (A6)	-0.033	0.160	0.177	-0.013	0.164	1.000

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Table 17: continued

		A1	A2	A3	A4	A5	A6
Floor	**Arrangement 1 (A1)**	1.000	0.998**	0.973**	0.871**	0.838**	0.852**
	Arrangement 2 (A2)	0.998**	1.000	0.974**	0.869**	0.817**	0.837**
	Arrangement 3 (A3)	0.973**	0.974**	1.000	0.893**	0.760**	0.774**
	Arrangement 4 (A4)	0.871**	0.869**	0.893**	1.000	0.656**	0.661**
	Arrangement 5 (A5)	0.838**	0.817**	0.760**	0.656**	1.000	0.995**
	Arrangement 6 (A6)	0.852**	0.837**	0.774**	0.661**	0.995**	1.000
		A1	**A2**	**A3**	**A4**	**A5**	**A6**
Desktop	**Arrangement 1 (A1)**	1.000	0.996	0.999*	0.999*	1.000**	0.981
	Arrangement 2 (A2)	0.996	1.000	0.999*	0.998*	0.997	0.995
	Arrangement 3 (A3)	0.999*	0.999*	1.000	1.000**	1.000*	0.989
	Arrangement 4 (A4)	0.999*	0.998*	1.000**	1.000	1.000*	0.988
	Arrangement 5 (A5)	1.000**	0.997	1.000*	1.000*	1.000	0.984
	Arrangement 6 (A6)	0.981	0.995	0.989	0.988	0.984	1.000

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Next, individual measurement points of fluorescent arrangements were grouped by surface and compared in SPSS. Correlation coefficient results per major surface are outlined in Table 19. For the north wall, only comparisons between Arrangement 2 and 4, and Arrangement 2 and 5 indicated no significant correlation. Similar to results from LED arrangements, east wall comparisons under fluorescent lighting show all comparisons involving Arrangement 6 had no significant correlation. All arrangements were statistically significant for at least the 0.05 level on the south wall. All arrangements involving Arrangement 6 and most of the arrangements involving Arrangement 2 had no significant correlation at the west wall. At the floor, all arrangements were statistically significant. Finally, all comparisons on the desktop had very strong correlation but not all displayed statistical significance. None of the comparisons involving Arrangement 6 were statistically significant at the desktop.

Table 18: Fluorescent arrangements correlation coefficients, luminance separated by surface

		A1	A2	A3	A4	A5	A6
North Wall	**Arrangement 1 (A1)**	1.000	0.445*	0.745**	0.935**	0.531*	0.449*
	Arrangement 2 (A2)	0.455*	1.000	0.484*	0.359	0.267	0.468*
	Arrangement 3 (A3)	0.745**	0.484*	1.000	0.697**	0.667**	0.667**
	Arrangement 4 (A4)	0.935**	0.359	0.697**	1.000	0.752**	0.629**
	Arrangement 5 (A5)	0.531*	0.267	0.667**	0.752**	1.000	0.923**
	Arrangement 6 (A6)	0.449*	0.468*	0.667**	0.629**	0.923**	1.000
		A1	**A2**	**A3**	**A4**	**A5**	**A6**
East Wall	**Arrangement 1 (A1)**	1.000	0.492**	0.820**	0.968**	0.908**	0.110
	Arrangement 2 (A2)	0.492**	1.000	0.494**	0.374*	0.352	0.236
	Arrangement 3 (A3)	0.820**	0.494**	1.000	0.876**	0.837**	0.342
	Arrangement 4 (A4)	0.968**	0.374*	0.876**	1.000	0.943**	0.124
	Arrangement 5 (A5)	0.908**	0.352	0.837**	0.943**	1.000	0.295
	Arrangement 6 (A6)	0.110	0.236	0.342	0.124	0.295	1.000
		A1	**A2**	**A3**	**A4**	**A5**	**A6**
South Wall	**Arrangement 1 (A1)**	1.000	0.868**	0.684**	0.889**	0.817**	0.798**
	Arrangement 2 (A2)	0.868**	1.000	0.704**	0.667**	0.711**	0.774**
	Arrangement 3 (A3)	0.684**	0.704**	1.000	0.689**	0.473*	0.491*
	Arrangement 4 (A4)	0.889**	0.667**	0.689**	1.000	0.574**	0.545*
	Arrangement 5 (A5)	0.817**	0.711**	0.473*	0.574**	1.000	0.980**
	Arrangement 6 (A6)	0.798**	0.774**	0.491*	0.545*	0.980**	1.000
		A1	**A2**	**A3**	**A4**	**A5**	**A6**
West Wall	**Arrangement 1 (A1)**	1.000	0.355	0.947**	0.951**	0.881**	-0.053
	Arrangement 2 (A2)	0.355	1.000	0.456*	0.157	0.117	0.239
	Arrangement 3 (A3)	0.947**	0.456*	1.000	0.895**	0.897**	0.172
	Arrangement 4 (A4)	0.951**	0.157	0.895**	1.000	0.944**	-0.045
	Arrangement 5 (A5)	0.881**	0.117	0.897**	0.944**	1.000	0.125
	Arrangement 6 (A6)	-0.053	0.239	0.172	-0.045	0.125	1.000

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Table 18: continued

		A1	A2	A3	A4	A5	A6
Floor	**Arrangement 1 (A1)**	1.000	0.988**	0.974**	0.881**	0.941**	0.944**
	Arrangement 2 (A2)	0.988**	1.000	0.969**	0.819**	0.934**	0.945**
	Arrangement 3 (A3)	0.974**	0.969**	1.000	0.895**	0.894**	0.896**
	Arrangement 4 (A4)	0.881**	0.819**	0.895**	1.000	0.767**	0.764**
	Arrangement 5 (A5)	0.941**	0.934**	0.894**	0.767**	1.000	0.994**
	Arrangement 6 (A6)	0.944**	0.945**	0.896**	0.764**	0.994**	1.000
		A1	**A2**	**A3**	**A4**	**A5**	**A6**
Desktop	**Arrangement 1 (A1)**	1.000	0.996	0.999*	1.000*	1.000**	0.973
	Arrangement 2 (A2)	0.996	1.000	0.999*	0.997*	0.996	0.991
	Arrangement 3 (A3)	0.999*	0.999*	1.000	1.000*	0.999*	0.982
	Arrangement 4 (A4)	1.000*	0.997*	1.000*	1.000	1.000*	0.978
	Arrangement 5 (A5)	1.000**	0.996	0.999*	1.000*	1.000	0.974
	Arrangement 6 (A6)	0.973	0.991	0.982	0.978	0.974	1.000

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

For visual comparison of the difference in luminance distribution between lighting arrangements, pseudo-color renderings were composed in AGI32. The pseudo-color scale maximum was set to 70 cd/m^2 for all arrangements to detail the luminance distribution across the space. The pseudo-color scale is depicted in Figure 14. Pseudo-color AGI32 renderings are shown in Figures 15. Images reveal fluorescent light sources caused slightly higher luminance levels on major surfaces. This trend is best observed at higher points on the major surfaces, closer to the luminaires. Rendered images suggest light distribution of LED light sources and fluorescent light sources are similar but not identical. Therefore, it can be assumed that the light source does impact the luminance distribution. Additionally, renderings reveal higher luminance values were present when luminaires were grouped together. Grouped arrangements tended to create hot-spots on higher portions of the walls. Lighting arrangements where luminaires were more dispersed resulted in more consistent luminance coverage.

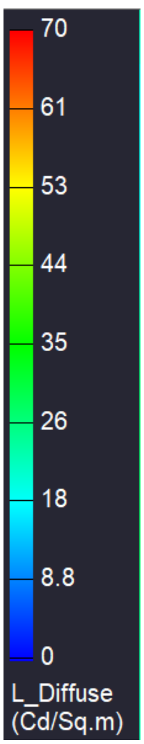
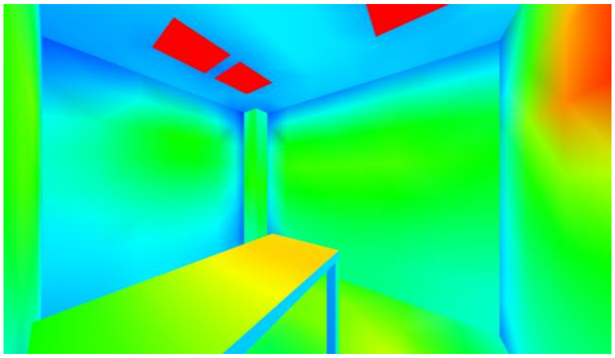
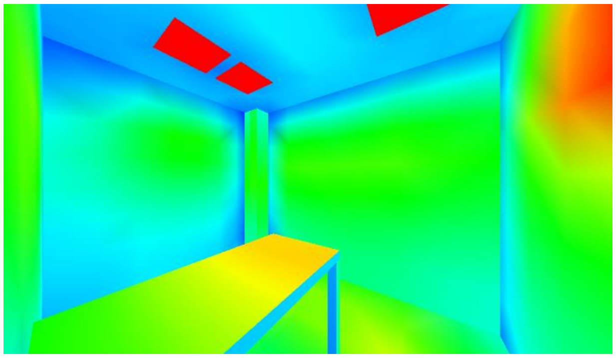


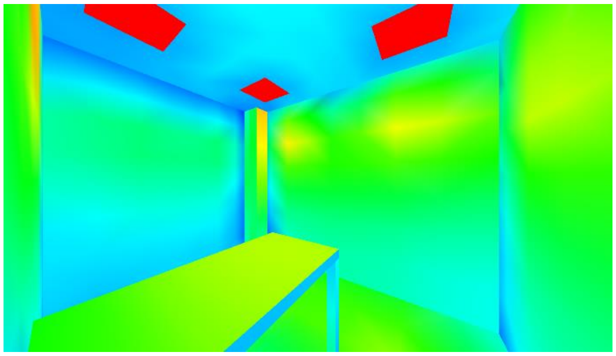
Figure 14: Pseudo-color luminance scale



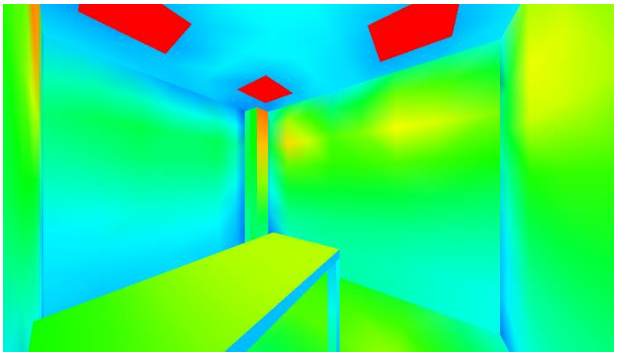
(a)



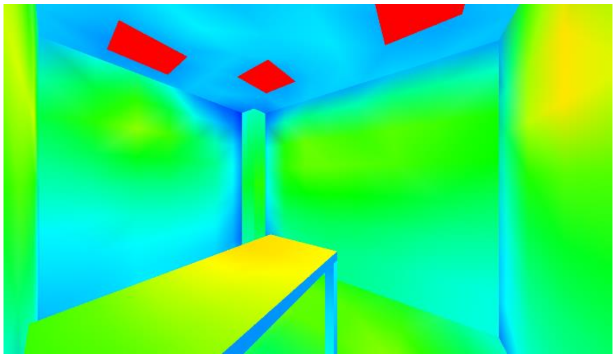
(b)



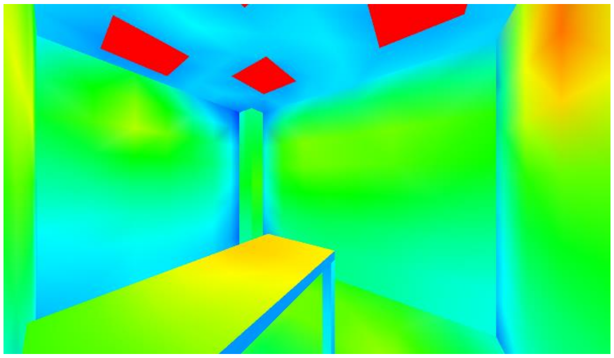
(c)



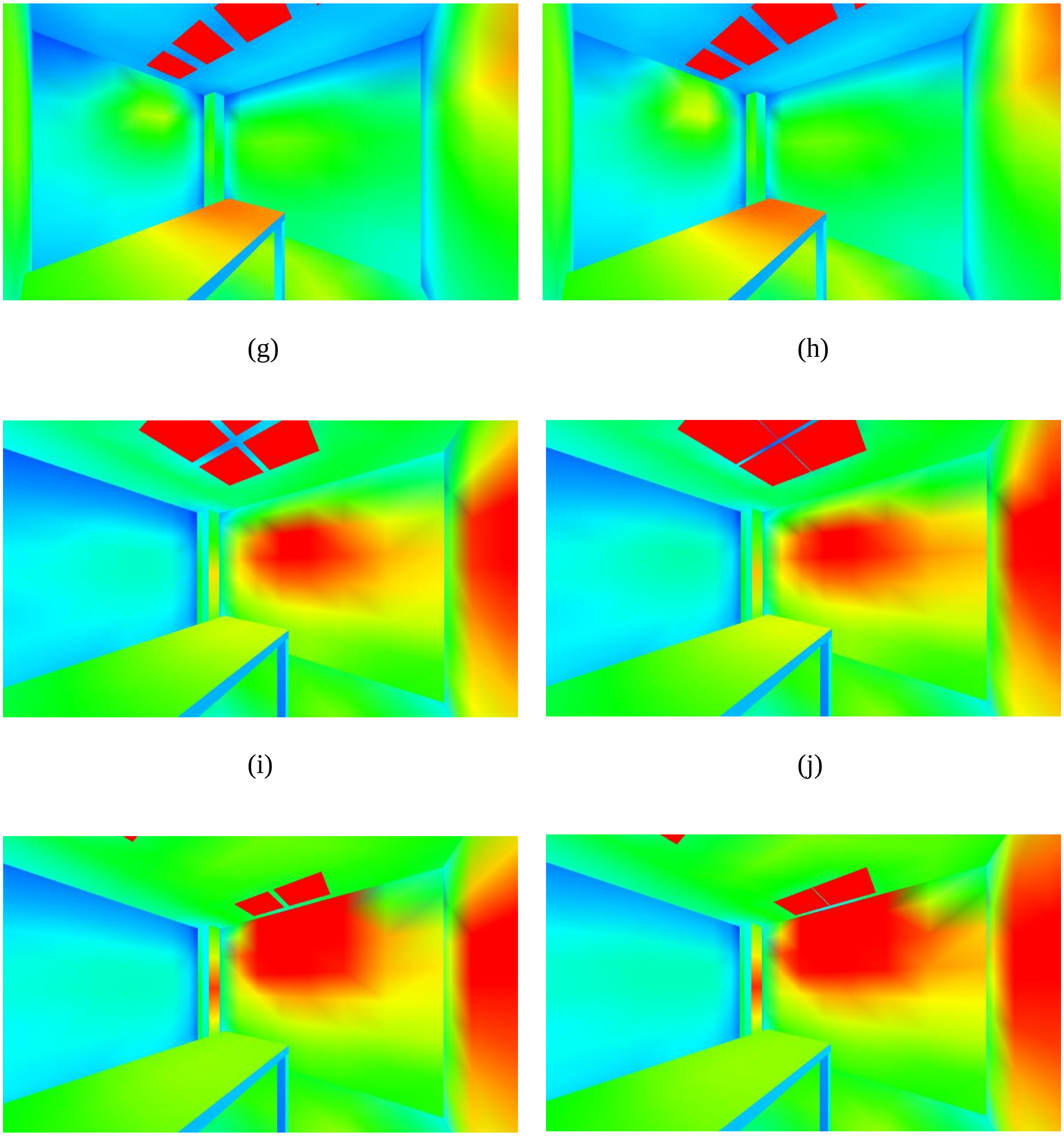
(d)



(e)



(f)



(k) (l)

Figure 15: Pseudo-color renderings of AGI32 lighting arrangements. (a) LED Arrangement 1, (b) Fluorescent Arrangement 1, (c) LED Arrangement 2, (d) Fluorescent Arrangement 2, (e) LED Arrangement 3, (f) Fluorescent Arrangement 3, (g) LED Arrangement 4, (h) Fluorescent Arrangement 4, (i) LED Arrangement 5, (j) Fluorescent Arrangement 5, (k) LED Arrangement 6, (l) Fluorescent Arrangement 6

4.3 STAGE 2 ANALYSIS – REAL LIT ENVIRONMENT

Stage 2 analysis was completed to determine luminance patterns resulting from individual lighting preferences by comparing light levels under the four testing conditions. Analyzed data was gathered from the sample group described in section 3.2.1.

4.3.1 TESTING ROOM MEASUREMENT POINTS

Figure 16 graphically depicts the average luminance levels of the 8 sample points. An average luminance level of approximately 36 cd/m^2 was maintained when lighting control was restricted. About 73% of participants preferred luminance levels under 36 cd/m^2 when given access to continuous dimming control.

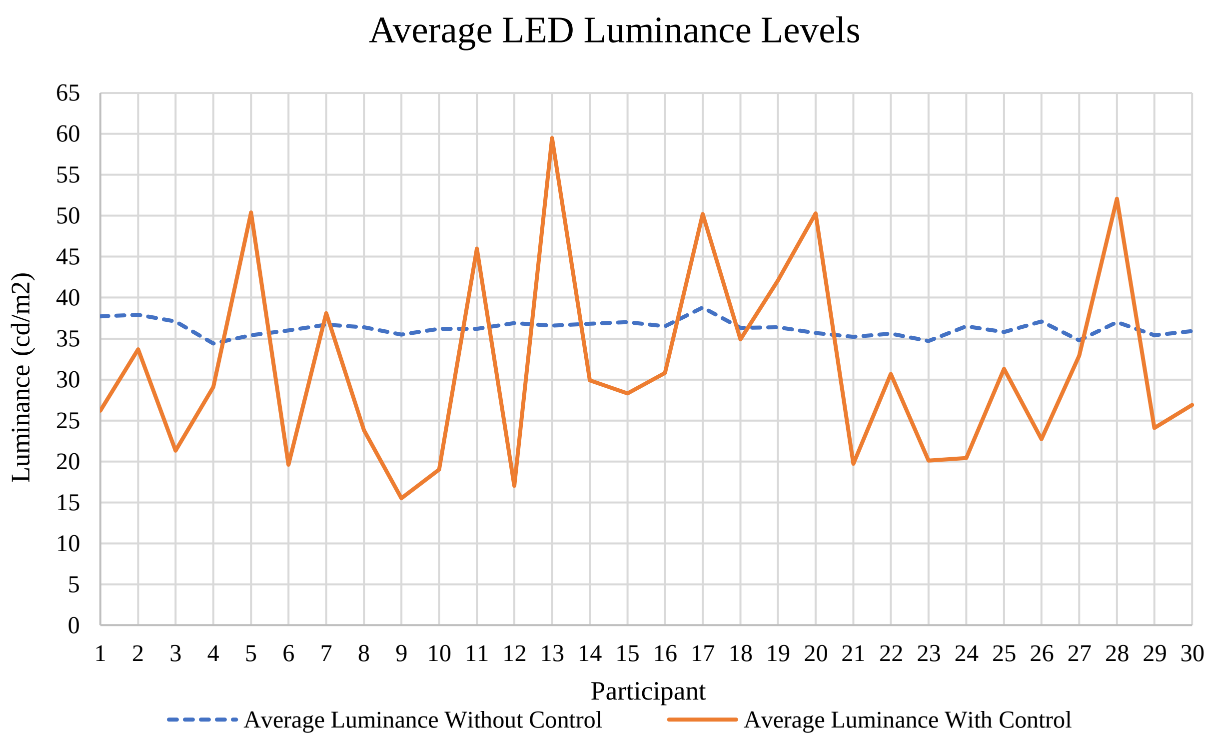


Figure 16: Control points luminance under LED lighting conditions

The illuminance data for the LED lighting system when participants were not given access to lighting control was first compared to the LED lighting system when participants were given access to lighting control. A strong correlation was found (r = 0.677) showing there was no significant difference between illuminance values across the eight sample points for all 30 participants. Next, data from all 30 participants was analyzed by individual measurement points. The correlation coefficient for illuminance values at each measurement point, when participants did not have access to lighting controls compared to when participants had access to lighting controls, are detailed in Table 19. Measurement point 1 and measurement point 2 were found to have a moderate correlation. All other measurement points concluded weak or very weak correlation indicating statistically significant differences in illuminance values across all 30 participants. The greatest differences are observed at measurement point 6.

Table 19: LED arrangements correlation coefficients, measurement point luminance for all participants

Measurement Point	Correlation Coefficient
1	0.577**
2	0.582**
3	-0.107
4	0.168
5	0.282
6	-0.118
7	-0.028
8	-0.208

** Correlation is significant at the 0.01 level (2-tailed)

To investigate if gender played a role in lighting preference, participant data was divided by gender. Figure 17 conveys the breakdown of participant lighting preference by gender. The majority of both males and females, accounting for over 63% of the total population, favored a decrease in the amount of general lighting with an increase in the amount of task lighting. Overall, almost 80% of female participants and 82% of male participants decreased the level of general lighting.

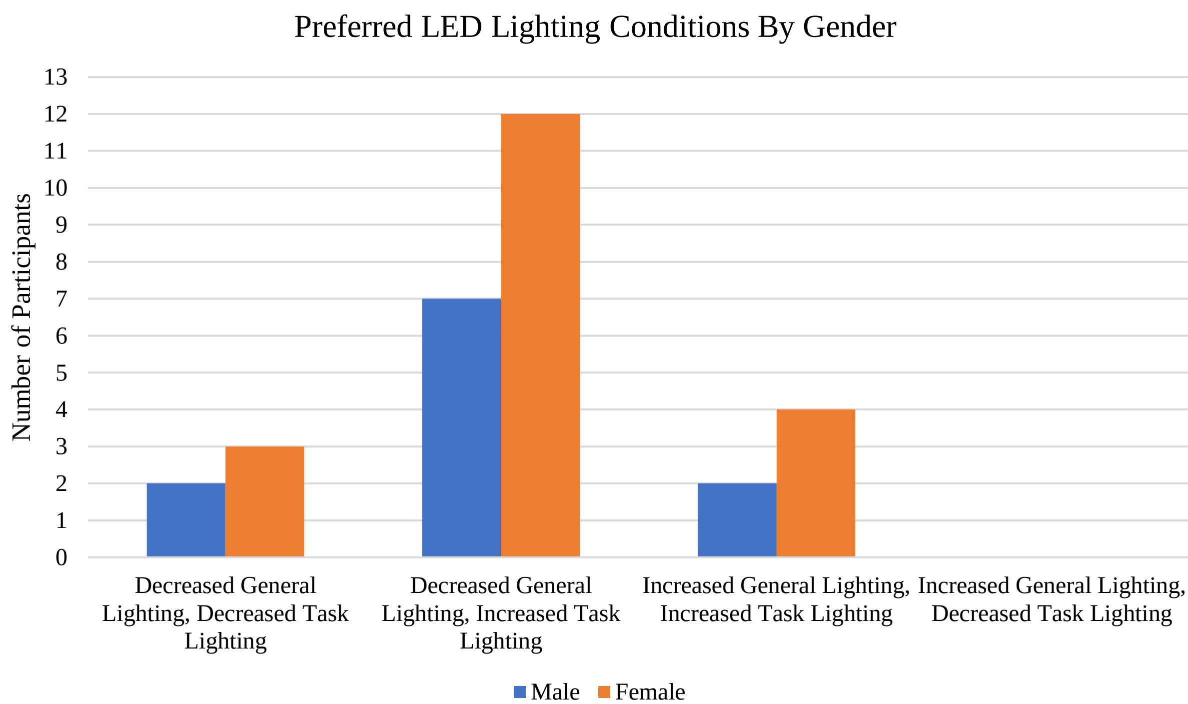


Figure 17: Preferred LED lighting conditions of participants by gender

Statistical analysis of gender results showed a strong relationship in illuminance levels across all eight measurement points exists between both male and female participants. Females (r = 0.711) were found to have a slightly stronger correlation than males (r = 0.621). Illuminance values from participant tests were then separated by both identified gender and measurement point. Results are outlined in Table 20. At measurement point 1, there was strong correlation among female data while male data had a moderate correlation. For both females and males, there was moderate correlation at point 2. Very weak correlation was concluded at measurement point 3 and measurement point 4 for males and females. At measurement point 5, female data determined very weak correlation while male correlation deduced strong correlation. Very weak correlation was present for females at point 6 and at point 7. Male correlation was found to be weak at point 6 and at point 7. Both male and female had very weak correlation at measurement point 8.

Table 20: LED arrangements correlation coefficients, measurement point luminance by participant gender

Measurement Point	Correlation Coefficient	
	Male	**Female**
1	0.457	0.623**
2	0.582	0.584**
3	0.055	-0.178
4	0.121	0.209
5	0.634*	0.065
6	-0.259	-0.053
7	-0.200	0.029
8	-0.141	-0.241

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

LED data was then analyzed based on visual acuity. Figure 18 graphically depicts a summary of participants preferred lighting conditions. About 78% of participants with 20/16 visual acuity and 57% of participants with 20/20 visual acuity preferred decreased general lighting and increased task lighting.

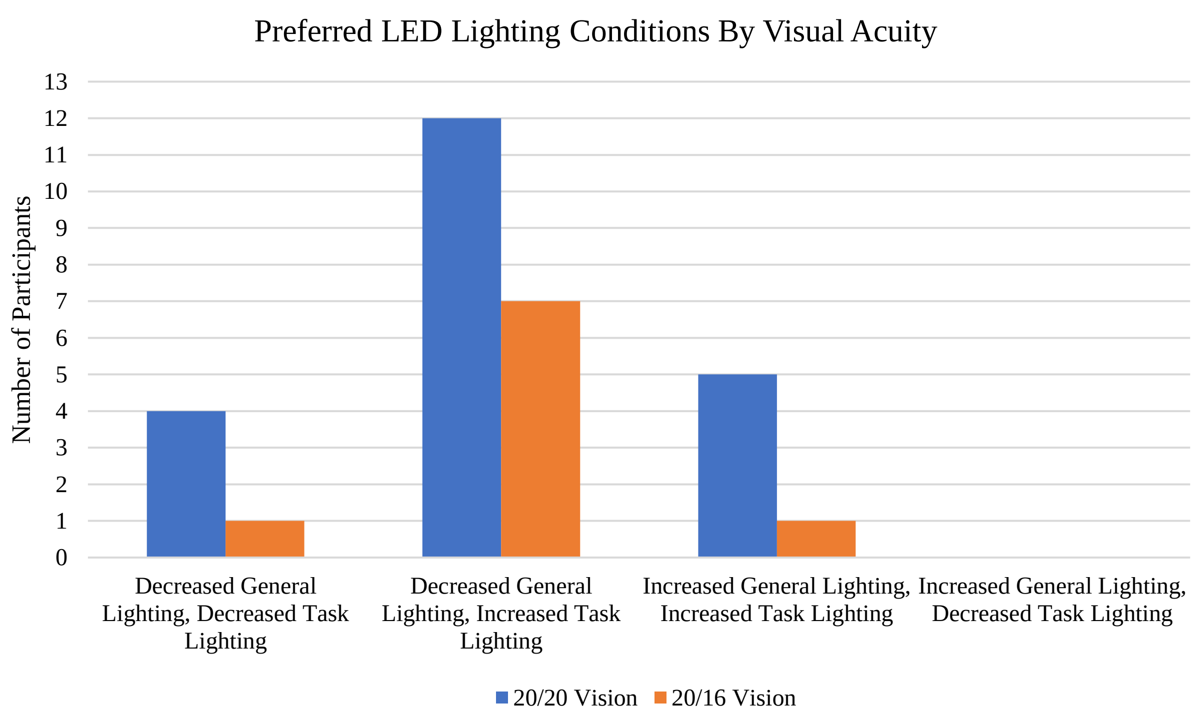


Figure 18: Preferred LED lighting conditions of participants by visual acuity

Next, LED illuminance results from the eight measurement points from each participant were statistically compared on a basis of visual acuity. Participants with 20/20 visual acuity were found to have a strong correlation (r = 0.683). Almost identical results were concluded from participants with 20/16 visual acuity (r = 0.668). Strong correlation was observed at measurement points 1 and 2 for 20/20 visual acuity. Both measurement points lie on the desktop. However, measurement points 6 and 7 for 20/16 visual acuity had a strong correlation. Detailed results of each measurement points are shown in Table 21.

Table 21: LED arrangements correlation coefficients, measurement point luminance by visual acuity

Measurement Point	Correlation Coefficient	
	20/20	**20/16**
1	0.641**	0.263
2	0.643**	-0.453
3	-0.031	-0.313
4	0.195	0.170
5	0.413	-0.044
6	-0.030	-0.646
7	0.117	-0.676*
8	-0.243	-0.143

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Next, fluorescent data was analyzed. The average luminance levels of the 8 sample points under fluorescent conditions is plotted in Figure 19. When access to lighting control was not provided, a luminance level of about 38 cd/m^2 was maintained. Roughly 63% of participants preferred lowered luminance levels.

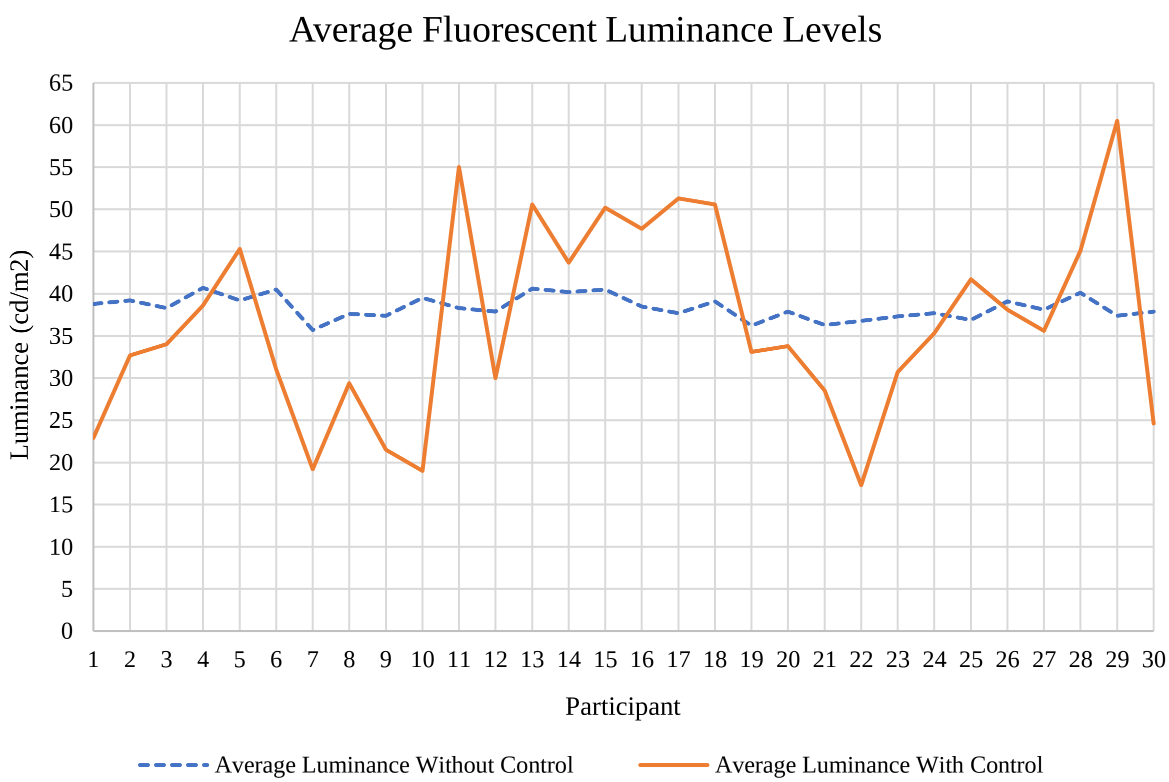


Figure 19: Control points luminance under fluorescent lighting conditions

Comparisons made between illuminance values of fluorescent lighting systems produced several of the same results as the illuminance values of LED lighting systems. There was a strong correlation (r = 0.633) between all 30 participants when comparing illuminance values across all eight sample points when participants were not allowed dimming control over a fluorescent lighting system to when participants were given dimming control over a fluorescent lighting system. Analysis was then performed at each measurement point for all 30 subjects. The results are outlined in Table 22. Results of measurement points 2, 4, 5, 6, and 7 conclude significant difference with measurement point 6 having the weakest correlation.

Table 22: Fluorescent arrangements correlation coefficients, measurement point luminance for all participants

Measurement Point	Correlation Coefficient
1	0.586^{**}
2	0.342
3	0.471^{**}
4	0.198
5	0.255
6	0.091
7	0.451^{*}
8	0.539^{**}

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Figure 20 graphically shows the breakdown of lighting preferences on account of gender. Preference amongst males were strongly in favor of decreased general lighting and increased task lighting. In contrast, only 32% of females preferred decreased general lighting and increased task lighting. Favoritism for females was evenly split between increased general lighting with increased task lighting, decreased general lighting with increased task lighting, and decreased general lighting with decreased task lighting.

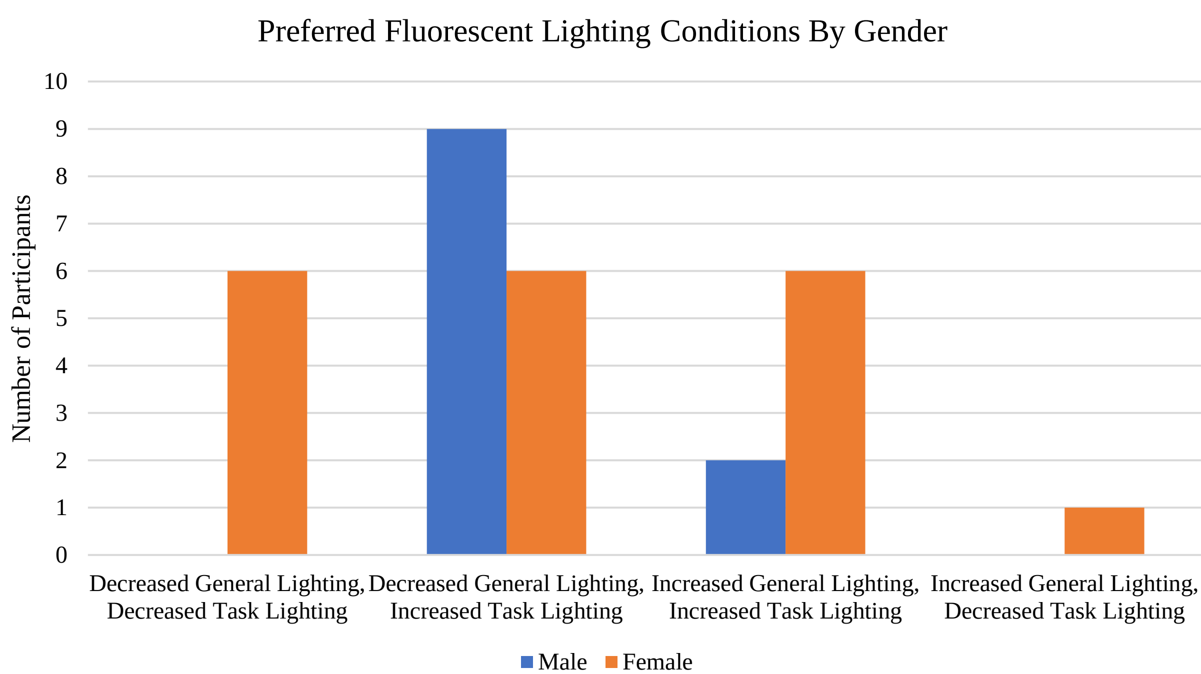


Figure 20: Preferred fluorescent lighting conditions of participants by gender

Statistical analysis of measurement points was then performed using the numerical data obtained from Li's study. Results conclude that females (r = 0.611) and males (r = 0.677) had similar correlation values when all points were compared. It can be stated that there is little statistical difference across all measurement points when compared by gender. A more in-depth analysis was completed to investigate the correlation at each of the eight measurement points according to gender. Correlation coefficient results is outlined in Table 23. For males, significant difference was observed at measurement point 2 and measurement point 5. Significant difference amongst females was observed at measurement points 2, 4, 5, 6, and 7.

Table 23: Fluorescent arrangements correlation coefficients, measurement point luminance by participant gender

Measurement Point	Correlation Coefficient	
	Male	**Female**
1	0.622*	0.644**
2	0.268	0.368
3	0.583	0.417
4	0.486	0.120
5	0.293	0.258
6	0.779**	-0.059
7	0.782**	0.229
8	0.693*	0.460*

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

A summary of fluorescent lighting preferences is illustrated in Figure 21. 50% of participants preferred decreased levels of general light and increased levels of task lighting. About 48% of participants with 20/20 visual acuity and 56% of participants with 20/16 visual acuity followed these preferences.

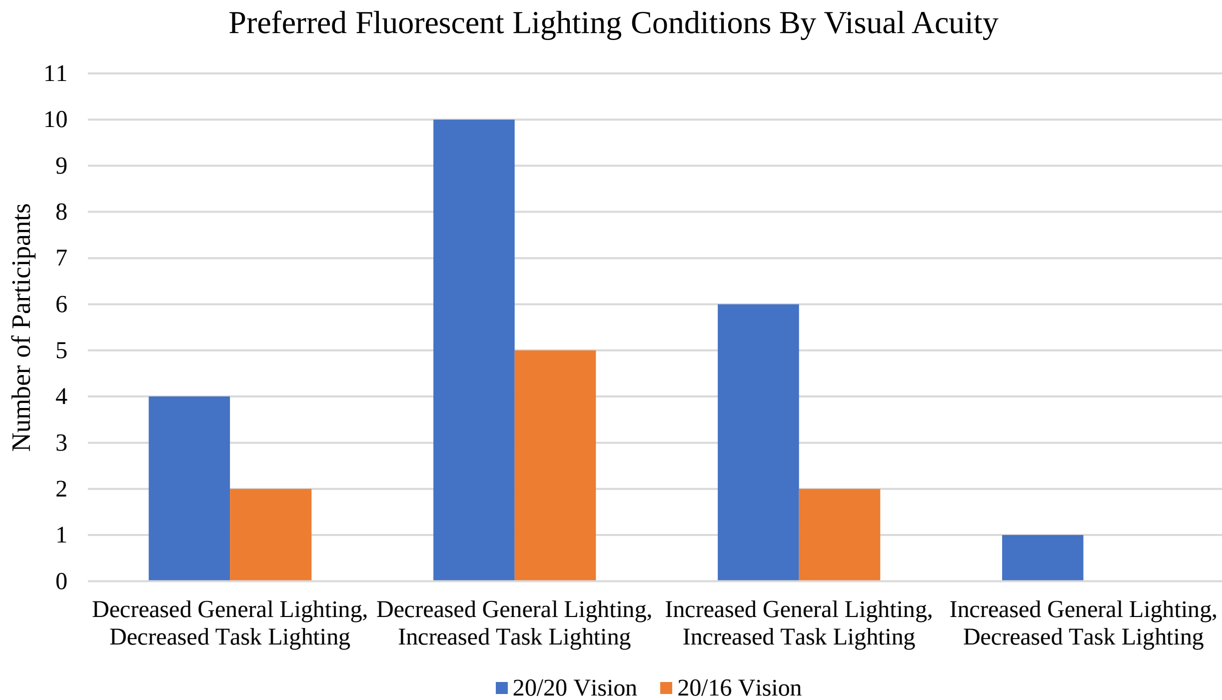


Figure 21: Preferred fluorescent lighting conditions of participants by visual acuity

Fluorescent illuminance results from the eight measurement points from each participant and compared on a basis of visual acuity. Participants with 20/20 visual acuity were found to have a strong correlation (r = 0.722) while participants with 20/16 visual acuity only had a moderate correlation (r = 0.425). The greatest contrast in correlation occurs at measurement point 1 and measurement point 7. At point 1, 20/20 participants had a strong correlation while 20/16 participants had a weak correlation. Opposed to results at point 6, where 20/16 participants had a strong correlation and 20/20 participants had a weak correlation. Complete analysis results are listed in Table 24.

Table 24: Fluorescent arrangements correlation coefficients, measurement point luminance by visual acuity

Measurement Point	Correlation Coefficient	
	20/20	20/16
1	0.729**	0.224
2	0.326	0.206
3	0.514*	0.404
4	0.156	0.242
5	0.112	0.601
6	0.447*	-0.047
7	0.363	0.853**
8	0.547*	0.760*

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

4.3.2 HDR IMAGING

LED data collected from HDR images was first analyzed. First, the luminance values for all measurement areas, of all 30 participants, were compared. Comparison found a strong correlation (r = 0.777) between LED lighting conditions. Next, luminance area data from HDR images was compared based on participant gender to investigate if gender impacted luminance preferences across the testing room. The compared conditions included: females without control and males without control, females with control and males with control, females without control and females with control, and males without control and males with control. Correlation results, indicate all the compared conditions have either a strong or very strong correlation, as outlined in Table 25.

Data was then split by visual acuity of participants. The following scenarios were compared: 20/20 visual acuity without control and 20/16 visual acuity without control, 20/20 visual acuity with control and 20/16 visual acuity with control, 20/20 visual acuity without control and 20/20 visual acuity with control, 20/16 visual acuity without control and 20/16 visual acuity with control. Results are shown in Table 26. All correlation coefficients were either strong or very strong.

Table 25: LED HDR images correlation coefficient, divided by gender

	Females without control	**Males with control**
Females with control	0.748^{**}	0.795^{**}
Males without control	0.806^{**}	0.848^{**}

** Correlation is significant at the 0.01 level (2-tailed)

Table 26: LED HDR images correlation coefficient, divided by visual acuity

	20/20 without control	20/16 with control
20/20 with control	0.761**	0.801**
20/16 without control	0.883**	0.831**

** Correlation is significant at the 0.01 level (2-tailed)

Luminance data from HDR images were then divided by subareas. Subareas along the same surfaces were combined to give a more accurate analysis of the luminance effects. Areas number 1, 44, and 45 were omitted from surface analysis as each corresponding surface only consisted of an individual measurement area. Table 27 details the results of comparison. Results indicate moderate correlation in luminance for both the north wall and the east wall. West wall results are on the cusp between weak and moderate. Luminance values of the ceiling comparatively had a strong correlation value. In contrast, luminance levels along the floor were weakly correlated. Desktop luminance values were found to be moderately correlated when comparing the two lighting control scenarios.

Table 27: LED HDR images correlation coefficients, divided by major surfaces

Surface	Correlation Coefficient
Ceiling	0.750**
East Wall	0.550**
Floor	0.323**
North Wall	0.463**
Desktop	0.476**
West Wall	0.396**

** Correlation is significant at the 0.01 level (2-tailed)

Combined surface areas underwent further evaluation by splitting data based on identified gender and eyesight. Strong correlation was found on the ceiling for females while males had a very strong correlation. North wall and desktop results concluded moderate correlation for females and strong correlation for males. Along the east wall, females were found to have moderate correlation whereas males had a strong correlation. The west wall results for females proved a weak relationship. For males there was a moderate relationship present. Weak correlation was found for both males and females on the floor.

Table 28: LED HDR images correlation coefficients, divided by major surfaces and gender

Surface	Correlation Coefficient	
	Male	Female
Ceiling	0.830**	0.718**
East Wall	0.654**	0.515**
Floor	0.352*	0.317*
North Wall	0.608**	0.415**
Desktop	0.641**	0.414**
West Wall	0.502**	0.366**

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Comparisons were then made based on the visual acuity of the participants. Table 29 displays the results. All participants either possessed 20/20 vision or 20/16 vision at the time of testing. Individuals possessing 20/20 vision are traditionally viewed as having normal vision. Those possessing 20/16 vision are believed to have the best possible visual acuity. For the ceiling, participants with 20/16 vision were found to have a very strong correlation of coefficient while participants with 20/20 vision had a strong correlation of coefficient. There was strong correlation along the east wall for 20/16 vision participants. Comparatively, participants with a visual acuity of 20/20 had moderate correlation. Both levels of visual acuity showed weak correlation across the floor and moderate correlation across the north wall. Strong correlation was evident for 20/16 vision participants on the desktop. 20/20 vision possessors showed moderate correlation. Lastly, results for 20/16 participants proved moderate correlation along the west wall while 20/20 participants proved weak correlation. Comparatively, participants with 20/16 vision made less drastic changes to the lighting levels than participants with 20/20 vision.

Table 29: LED HDR images correlation coefficients, divided by major surfaces and visual acuity

Wall Section	**Correlation Coefficient**	
	20/20	**20/16**
Ceiling	0.734**	0.808**
East Wall	0.530**	0.633**
Floor	0.328**	0.249
North Wall	0.434**	0.578**
Desktop	0.443**	0.642**
West Wall	0.379**	0.447**

** Correlation is significant at the 0.01 level (2-tailed)

Once LED analysis was completed, HDR images detailing fluorescent layouts were analyzed. Luminance comparisons made between the following conditions: females without control and males without control, females with control and males with control, females without control and females with control, and males without control and males with control. Table 30 contains comparison results.

For visual acuity comparison, four conditions were compared: 20/20 visual acuity without control and 20/16 visual acuity without control, 20/20 visual acuity with control and 20/16 visual acuity with control, 20/20 visual acuity without control and 20/20 visual acuity with control, 20/16 visual acuity without control and 20/16 visual acuity with control. Results are outlined in Table 31.

Table 30: Fluorescent HDR images correlation coefficient, divided by gender

	Females without control	**Males with control**
Females with control	0.762^{**}	0.573^{**}
Males without control	0.820^{**}	0.665^{**}

** Correlation is significant at the 0.01 level (2-tailed)

Table 31: Fluorescent HDR images correlation coefficient, divided by visual acuity

	20/20 without control	**20/16 with control**
20/20 with control	0.777^{**}	0.554^{**}
20/16 without control	0.836^{**}	0.589^{**}

** Correlation is significant at the 0.01 level (2-tailed)

Luminance levels of major surfaces for all 30 participants were simultaneously compared for the two fluorescent lighting conditions. There was a strong correlation (r = 0.777) across all surfaces between luminance values when participants were not given access to lighting control and when participants were given access to lighting control. Data was then separated to find the correlation of each major surface. Results of the comparisons are outlined in Table 32. The north wall, west wall, floor, and desktop all concluded weak correlation. The east wall had moderate correlation when comparing lighting conditions. The ceiling was found to have the strongest correlation. It is hypothesized that correlation along the ceiling is the highest due to the majority of light being emitted from ceiling fixtures.

Table 32: Fluorescent HDR images correlation coefficients, divided by major surfaces

Wall Section	Correlation Coefficient
Ceiling	0.700**
East Wall	0.447**
Floor	0.262*
North Wall	0.391**
Desktop	0.373**
West Wall	0.330**

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Table 33 depicts the correlation results when major surfaces data was subdivided by participant gender. Females had stronger correlation values than males at every major surface, meaning females had more consistent lighting level preferences than males. For both male and female, the strongest correlation was observed at the ceiling and the weakest correlation was observed at the floor.

Table 33: Fluorescent HDR images correlation coefficients, divided by major surfaces and gender

Wall Section	**Correlation Coefficient**	
	Male	**Female**
Ceiling	0.632^{**}	0.738^{**}
East Wall	0.334^{**}	0.521^{**}
Floor	0.115	0.377^{**}
North Wall	0.255^{*}	0.475^{**}
Desktop	0.269	0.445^{**}
West Wall	0.198^{*}	0.423^{**}

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Table 34 shows the correlation results when major surface data was subdivided by visual acuity of participants. Excluding the ceiling, correlation coefficients for participants with 20/16 visual acuity fell within the very weak range. Moderate correlation was found at the ceiling. For participants with 20/20 visual acuity, moderate correlation was observed across all major surfaces except the ceiling. A strong correlation was present at the ceiling. The greatest difference in lighting level preferences was seen at the floor for 20/20 visual acuity. Contrastingly, for 20/16 visual acuity, the west wall saw the most variance in lighting levels.

Table 34: Fluorescent HDR images correlation coefficients, divided by major surfaces and visual acuity

Wall Section	**Correlation Coefficient**	
	20/20	**20/16**
Ceiling	0.754**	0.544**
East Wall	0.554**	0.132
Floor	0.418**	-0.197
North Wall	0.502**	0.069
Desktop	0.480**	0.068
West Wall	0.457**	-0.065

** Correlation is significant at the 0.01 level (2-tailed)

* Correlation is significant at the 0.05 level (2-tailed)

Analysis of individual area luminance values provided an even greater depiction of how luminance differed when participants to their preferred conditions. A summary table of luminance measurement area locations if offered in Table 35 for reference throughout the following analyses. All correlation values were generated by comparing area luminances when participants were not given access to lighting control to when participants were given access to lighting control. The correlation results comparing all 30 participants under LED lighting systems are shown in Table 36. Results at all measured luminance areas concluded no significant correlation. All results deduce a weak or very weak correlation.

Table 37 outlines the correlation results of the measured luminance area by both gender and visual acuity. Measurement area 4 for males showed significant correlation. Most of the remaining measurement area locations had a weak or very weak correlation. All measured areas for females proved insignificant correlation. No significant correlation could be concluded when data was separated by visual acuity.

Table 35: HDR image area breakdown

Area Number	Location
1	Computer Screen
2	Whiteboard
3	Front wall, under board, left
4	Front wall, under board, right
5	Front bare wall (above computer)
6	Front bare wall (right corner)
7	Front bare wall (top of board)
8	Above door
9	Door
10	Right of door, no clock, above switch
11	Right of door, around switch, above table
12	Right of table leg
13	Under table
14	Gray trim, right of table
15	Upper, above lamp
16	Left of lamp head
17	Right of lamp head
18	Left of diagonal arm
19	Left, above board
20	Right, above board
21	Left board
22	Right board
23	Gray Trim
24	Left below board
25	Right below board
26	Top right tile
27	Top middle tile
28	Top Left Tile
29	Center right tile
30	Center middle tile
31	Center left tile
32	Right front tile
33	Middle front tile
34	Left front tile
35	Left Luminaire
36	Right Luminaire
37	Right of chin rest
38	Left of chin rest to table edge
39	Left of table
40	Under computer, right of keyboard
41	Under keyboard, no chin rest
42	Under computer, left of keyboard
43	Keyboard
44	Color checker
45	Paper on stand

Table 36: LED HDR area luminance correlation coefficients of all subjects

Measurement Area	Correlation Coefficient
1	0.068
2	-0.058
3	0.123
4	0.345
5	-0.111
6	-0.103
7	-0.113
8	-0.094
9	-0.103
10	-0.097
11	-0.076
12	-0.116
13	0.235
14	-0.033
15	-0.128
16	-0.140
17	0.019
18	-0.093
19	-0.095
20	-0.084
21	-0.036
22	-0.082
23	-0.064
24	-0.021
25	-0.054
26	0.107
27	0.102
28	0.103
29	-0.103
30	-0.104
31	-0.094
32	-0.102
33	-0.085
34	-0.082
35	-0.177
36	0.131
37	-0.037
38	0.032
39	-0.069
40	-0.126
41	-0.082
42	0.111
43	0.013
44	-0.039
45	-0.022

Table 37: LED HDR area luminance correlation coefficients divided by gender and visual acuity

Measurement Area	Correlation Coefficient			
	Male	Female	20/20	20/16
1	0.077	0.079	0.046	0.412
2	-0.051	-0.070	-0.039	-0.628
3	-0.202	0.173	0.019	0.324
4	0.652*	0.192	0.376	-0.065
5	-0.282	-0.092	-0.076	-0.490
6	-0.252	-0.089	-0.073	-0.518
7	-0.173	-0.122	-0.092	-0.541
8	-0.285	-0.069	-0.053	-0.590
9	-0.312	-0.078	-0.067	-0.535
10	-0.250	-0.077	-0.06	-0.575
11	-0.170	-0.065	-0.043	-0.526
12	-0.195	-0.121	-0.096	-0.412
13	0.255	0.222	0.325	-0.330
14	-0.046	-0.041	-0.067	-0.003
15	-0.235	-0.134	-0.103	-0.561
16	-0.288	-0.121	-0.110	-0.507
17	0.073	-0.008	0.002	-0.429
18	-0.359	-0.059	-0.050	-0.568
19	-0.217	-0.086	-0.066	-0.577
20	-0.240	-0.068	-0.056	-0.494
21	-0.148	-0.024	-0.005	-0.548
22	-0.171	-0.078	-0.059	-0.541
23	-0.112	-0.056	-0.098	-0.036
24	-0.221	0.008	0.000	-0.173
25	-0.213	-0.023	-0.021	-0.537
26	0.279	0.022	0.192	-0.639
27	0.250	0.027	0.187	-0.654
28	0.198	0.037	0.192	-0.515
29	-0.273	-0.081	-0.062	-0.593
30	-0.283	-0.082	-0.067	-0.571
31	-0.282	-0.071	-0.056	-0.590
32	-0.223	-0.089	-0.065	-0.569
33	-0.231	-0.073	-0.056	-0.528
34	-0.235	-0.068	-0.054	-0.513
35	0.407	-0.393	-0.127	-0.616
36	0.031	0.147	0.171	-0.214
37	-0.390	0.040	0.026	-0.578
38	-0.220	0.070	0.072	-0.390
39	-0.265	-0.044	-0.028	-0.629
40	-0.212	-0.122	-0.099	-0.432
41	0.428	-0.203	-0.117	-0.070
42	-0.002	0.174	0.116	-0.155
43	0.059	-0.014	0.014	-0.136
44	-0.091	0.007	-0.070	-0.010
45	-0.114	0.078	-0.028	-0.140

* Correlation is significant at the 0.05 level (2-tailed)

Table 38 details the correlation coefficient values of fluorescent lighting system conditions of all 30 participants. Like LED results, fluorescent results concluded no significant correlation at any of the 45 luminance measurement areas. All coefficients values fall within the very weak correlation category. Results point to limited similarities in lighting preferences between participants once given access to continuous dimming control.

Table 39 conveys the correlation coefficient results when measurement area luminance values under fluorescent lighting was divided by gender. Comparison results concluded no significant correlation at any measurement area location for either male or female. Coefficient results when comparing measurement area luminances values under fluorescent lighting systems divided by visual acuity are also depicted in Table 39. Only measurement point 4 for participants with 20/16 visual acuity proved to have significant correlation.

Table 38: Fluorescent HDR area luminance correlation coefficients of all subjects

Measurement Area	Correlation Coefficient
1	-0.046
2	-0.011
3	0.014
4	0.054
5	-0.033
6	-0.032
7	-0.058
8	-0.017
9	-0.026
10	-0.006
11	0.023
12	-0.029
13	0.010
14	-0.133
15	0.012
16	-0.036
17	0.188
18	-0.050
19	-0.018
20	-0.019
21	-0.019
22	0.013
23	-0.117
24	-0.035
25	0.000
26	-0.017
27	-0.019
28	-0.156
29	-0.033
30	-0.034
31	-0.022
32	-0.038
33	-0.021
34	-0.012
35	-0.005
36	-0.001
37	0.031
38	0.052
39	-0.013
40	0.026
41	-0.039
42	0.041
43	-0.024
44	0.012
45	-0.029

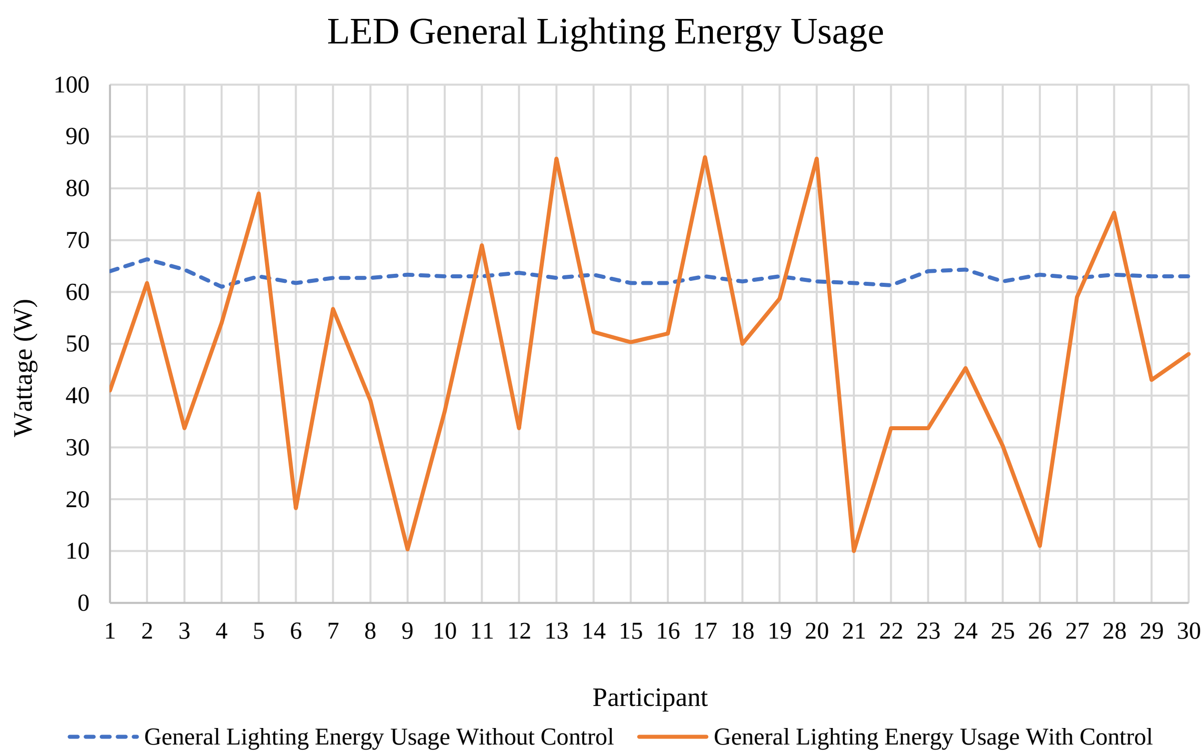
Table 39: Fluorescent HDR area luminance correlation coefficients divided by gender and visual acuity

Measurement Area	Correlation Coefficient			
	Male	Female	20/20	20/16
1	-0.220	0.116	0.132	-0.598
2	-0.176	0.103	0.180	-0.591
3	-0.173	0.130	0.190	-0.548
4	-0.447	0.283	0.237	-0.688*
5	-0.213	0.086	0.159	-0.619
6	-0.213	0.058	0.155	-0.622
7	-0.239	0.057	0.132	-0.607
8	-0.170	0.097	0.183	-0.603
9	-0.182	0.083	0.173	-0.635
10	-0.180	0.111	0.190	-0.612
11	-0.164	0.147	0.214	-0.608
12	-0.233	0.102	0.183	-0.659
13	-0.518	0.292	0.138	-0.391
14	-0.146	-0.131	0.076	-0.386
15	-0.157	0.121	0.207	-0.589
16	-0.170	0.080	0.156	-0.661
17	0.016	0.314	0.358	-0.529
18	-0.246	0.083	0.149	-0.630
19	-0.179	0.105	0.182	-0.627
20	-0.211	0.107	0.175	-0.597
21	-0.188	0.099	0.166	-0.603
22	-0.124	0.121	0.194	-0.576
23	-0.159	-0.117	0.068	-0.373
24	-0.216	0.102	0.159	-0.607
25	-0.177	0.111	0.162	-0.550
26	-0.201	0.108	0.162	-0.514
27	-0.156	0.098	0.187	-0.597
28	-0.568	0.119	-0.007	-0.606
29	-0.202	0.084	0.176	-0.638
30	-0.206	0.082	0.164	-0.612
31	-0.201	0.098	0.177	-0.611
32	-0.189	0.071	0.166	-0.650
33	-0.186	0.090	0.171	-0.617
34	-0.181	0.099	0.193	-0.624
35	-0.193	0.125	0.188	-0.649
36	-0.141	0.103	0.176	-0.562
37	-0.155	0.173	0.234	-0.520
38	-0.056	0.172	0.260	-0.543
39	-0.185	0.118	0.189	-0.627
40	-0.113	0.135	0.216	-0.585
41	-0.163	0.039	0.130	-0.500
42	-0.085	0.146	0.216	-0.563
43	-0.192	0.098	0.174	-0.532
44	-0.104	0.118	0.087	-0.458
45	-0.101	0.009	0.006	-0.225

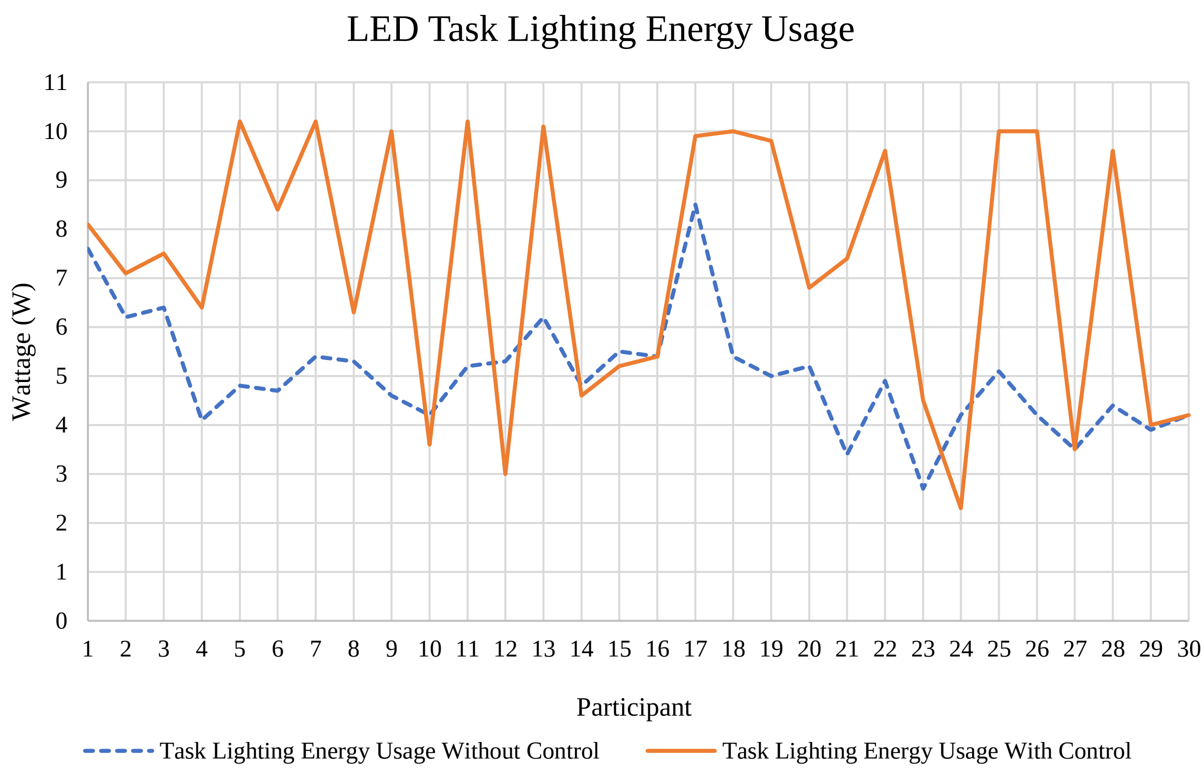
* Correlation is significant at the 0.05 level (2-tailed)

4.4 ENERGY ANALYSIS

LED lighting energy usage data is plotted in Figure 22. Data illustrates decreased general lighting energy usage and increased task lighting energy usage. The conclusion suggests that the majority of participants preferred decreased general lighting levels and increased task lighting levels. Energy consumed by the general lighting, on average, was about 63W when participants were not given lighting control. An energy reduction of almost 24% was observed in general lighting when participants were given lighting control. In contrast, task lighting had an average energy consumption of approximately 5W without lighting control. A 45% increase in task lighting energy usage was observed with lighting control was permitted.



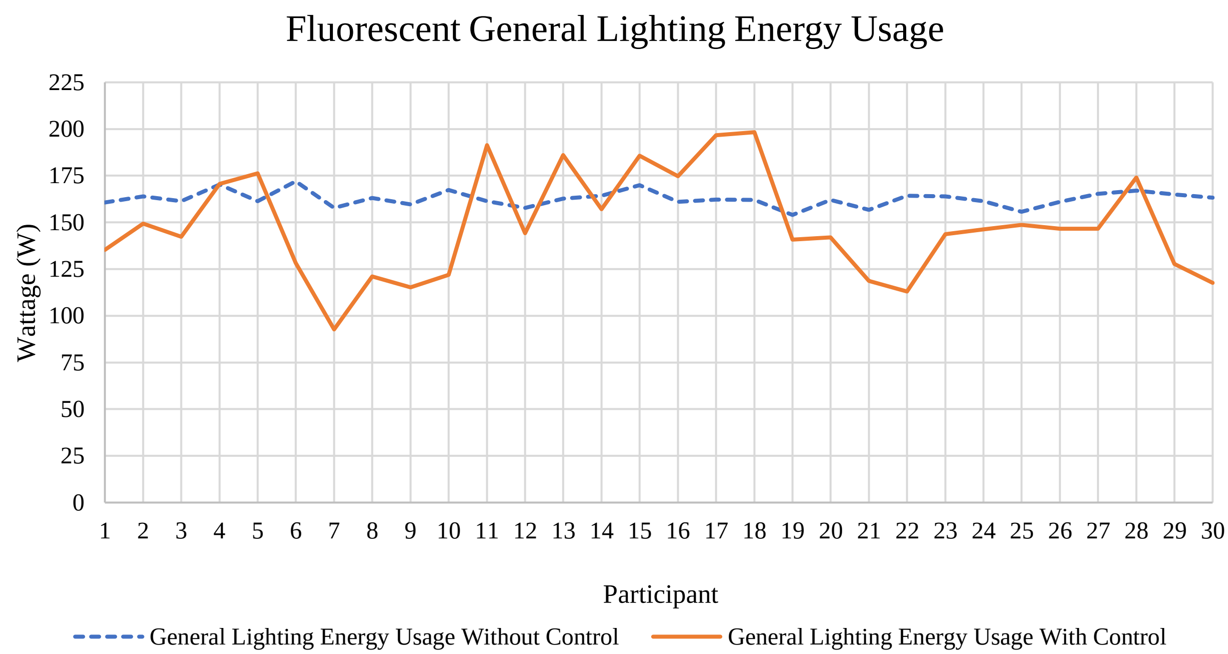
(a)



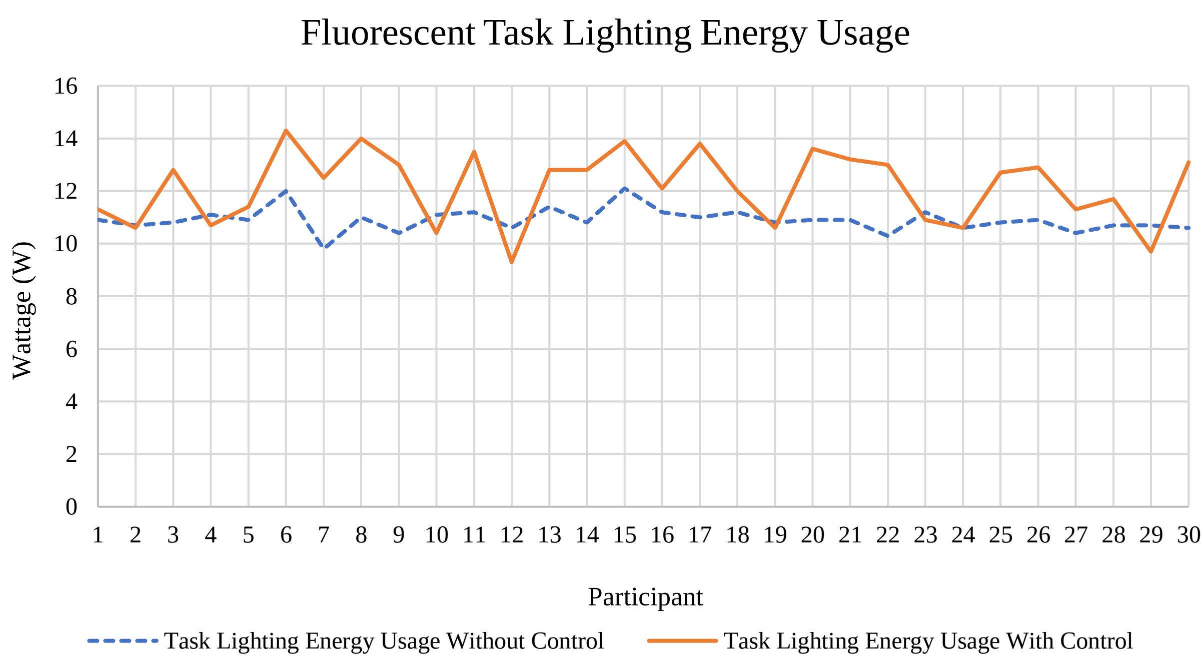
(b)

Figure 22: LED lighting energy usage. (a) General lighting, (b) Task lighting

Graphic illustrations of the fluorescent energy data, shown in Figure 23, exemplified similar patterns to LED energy usage. Partiality was given towards decreased general lighting energy usage and increased task lighting energy usage, although at a lesser degree than LED. Energy usage data indicates many participants tended to reduce general lighting levels and increase task lighting levels. A consistent general lighting energy usage of approximately 163W and a task lighting energy usage of 11W was observed when participants were not given access to lighting control. An energy decrease of almost 9% in general lighting and an energy increase of about 12% in task lighting was witnessed once participants were able to adjust lighting levels.



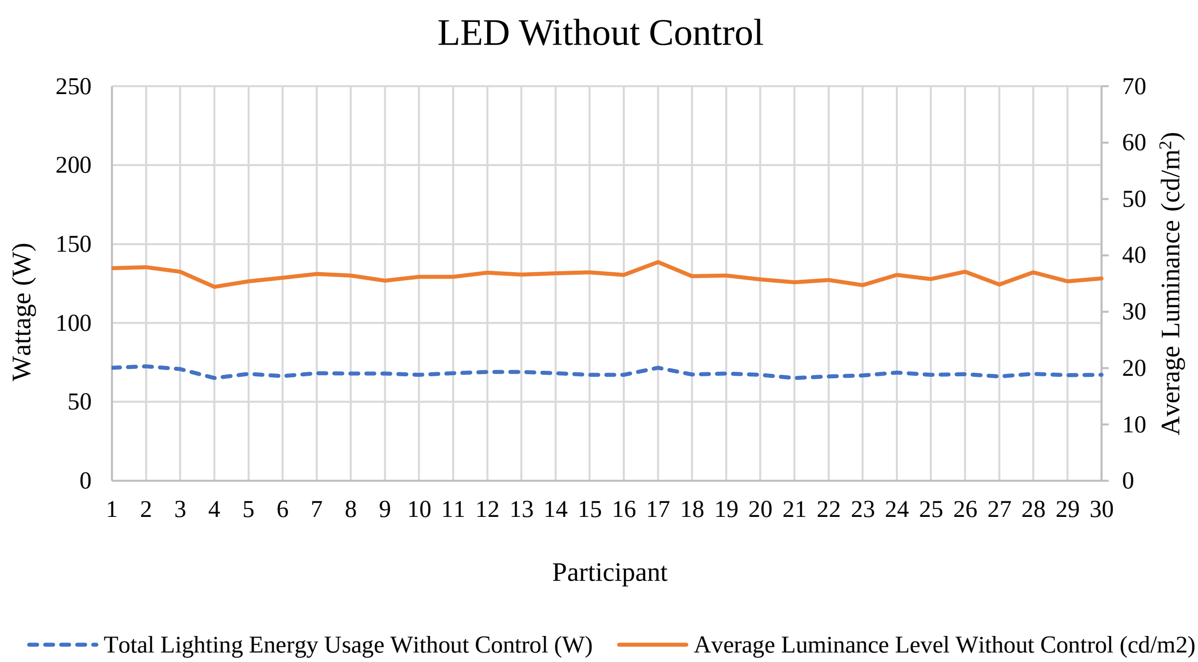
(a)



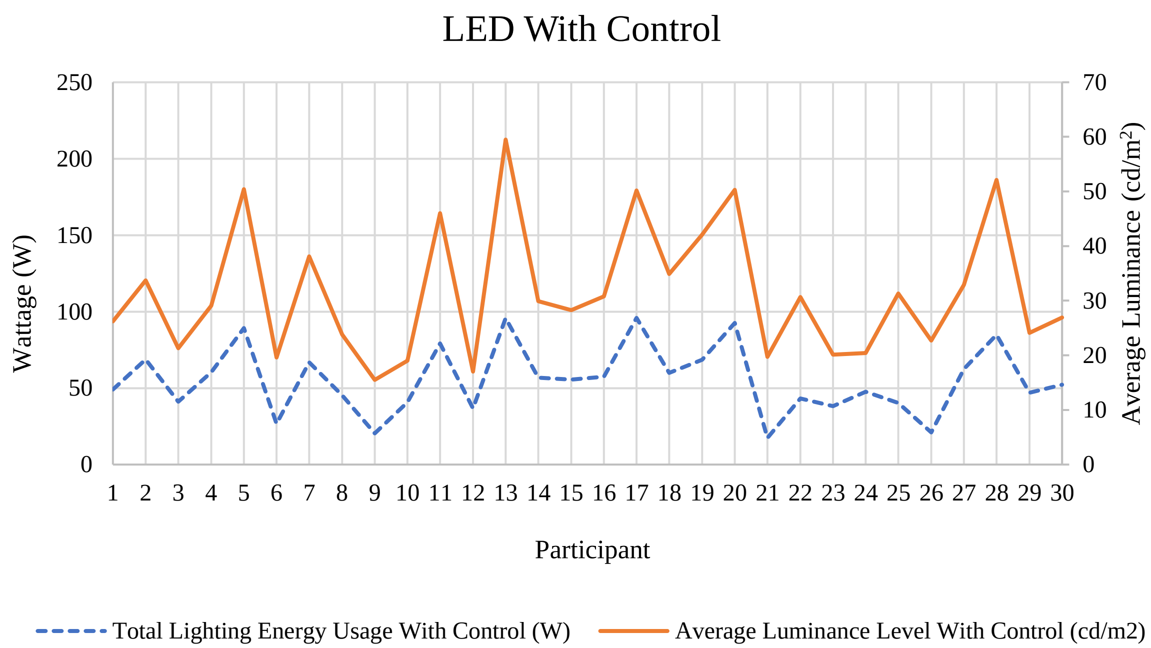
(b)

Figure 23: Fluorescent lighting energy usage. (a) General lighting, (b) Task lighting

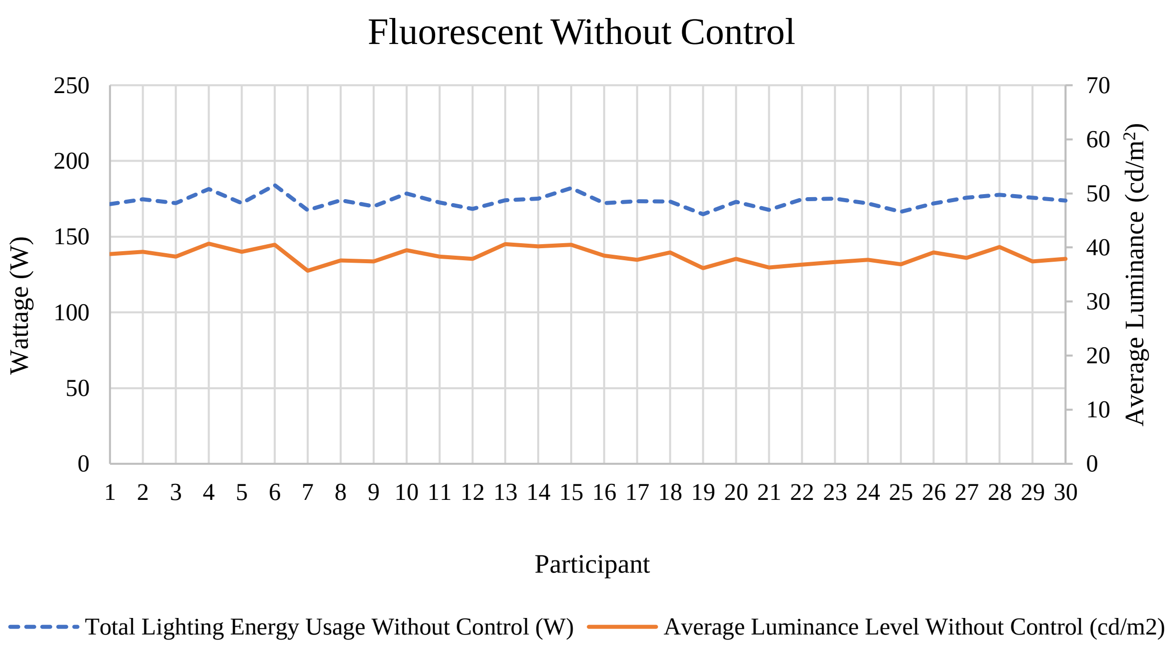
The relationship between average luminance of measurement points and energy usage is best expressed in Figure 24. The wattage level shown in the graph is a combination of the power consumed by the general lighting and the task lighting. Graphs illustrate a direct correlation between average luminance and energy usage. As average luminance increases, the total lighting energy of the space also increases.



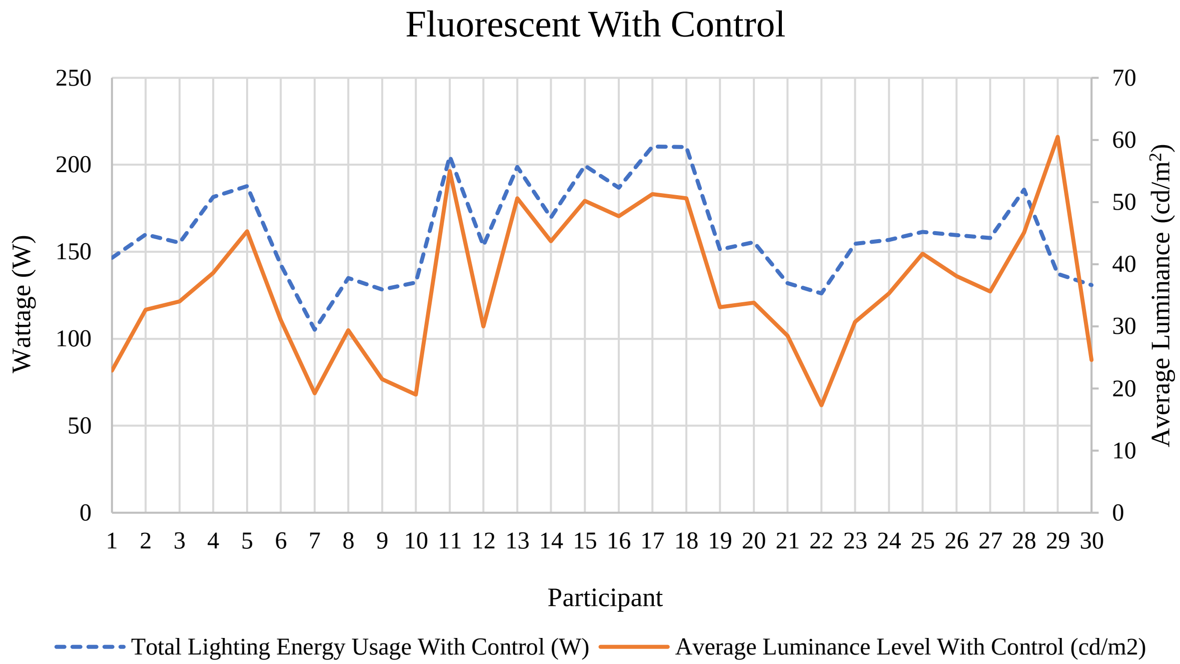
(a)


LED With Control
Wattage (W)
Average Luminance (cd/m^2)
Participant
Total Lighting Energy Usage With Control (W)
Average Luminance Level With Control (cd/m2)

(b)


Fluorescent Without Control
Wattage (W)
Average Luminance (cd/m^2)
Participant
Total Lighting Energy Usage Without Control (W)
Average Luminance Level Without Control (cd/m2)

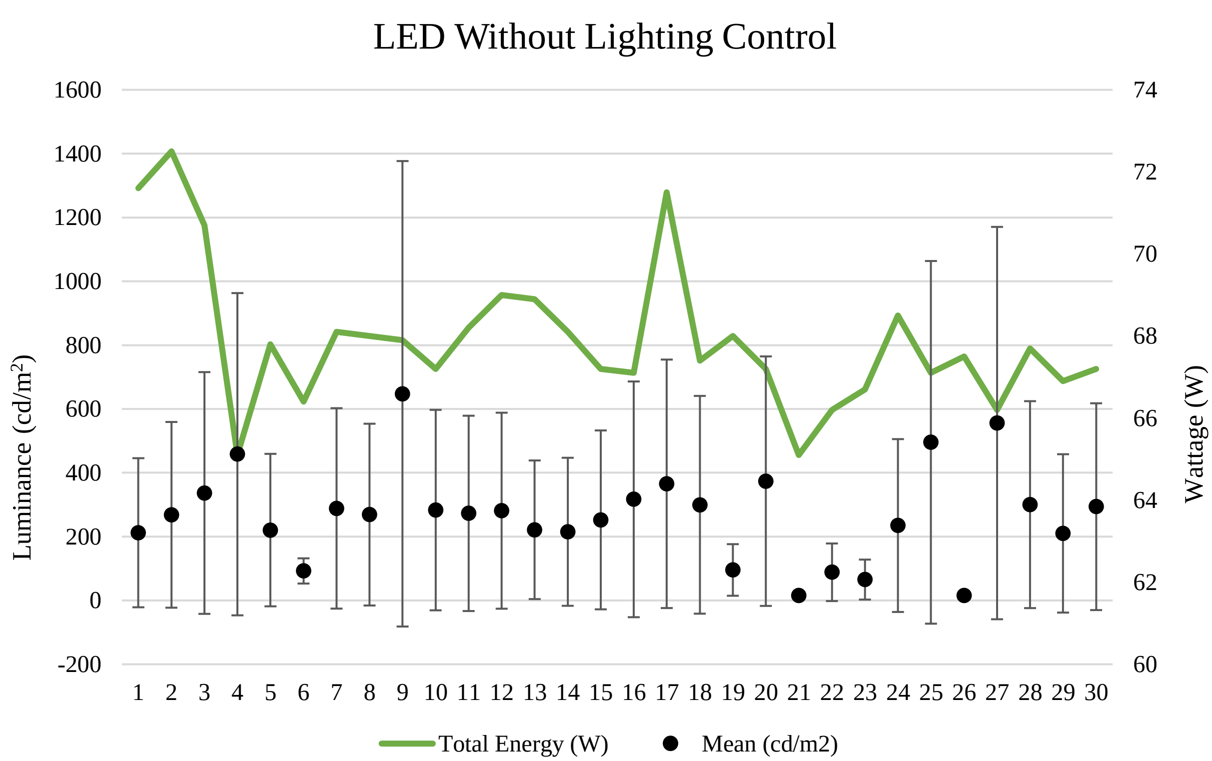
(c)



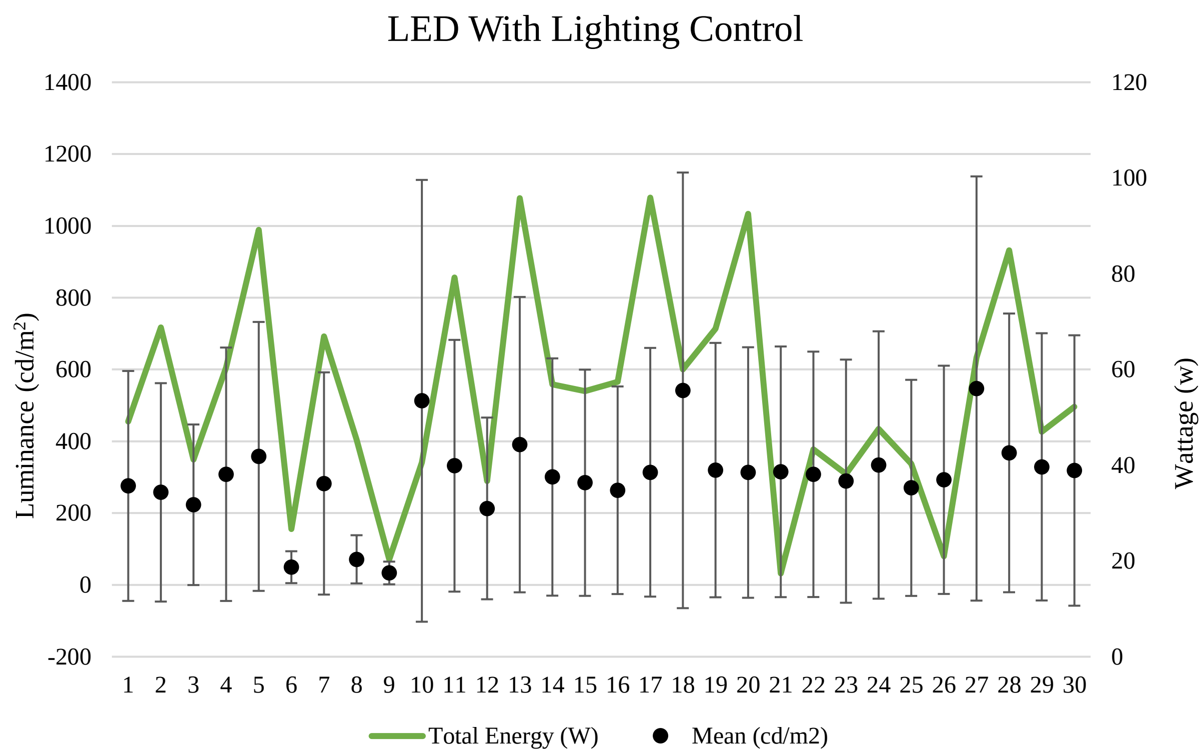
(d)

Figure 24: Average measurement point luminance and total energy usage. (a) LED without lighting control, (b) LED with lighting control, (c) Fluorescent without lighting control, (d) Fluorescent with lighting control

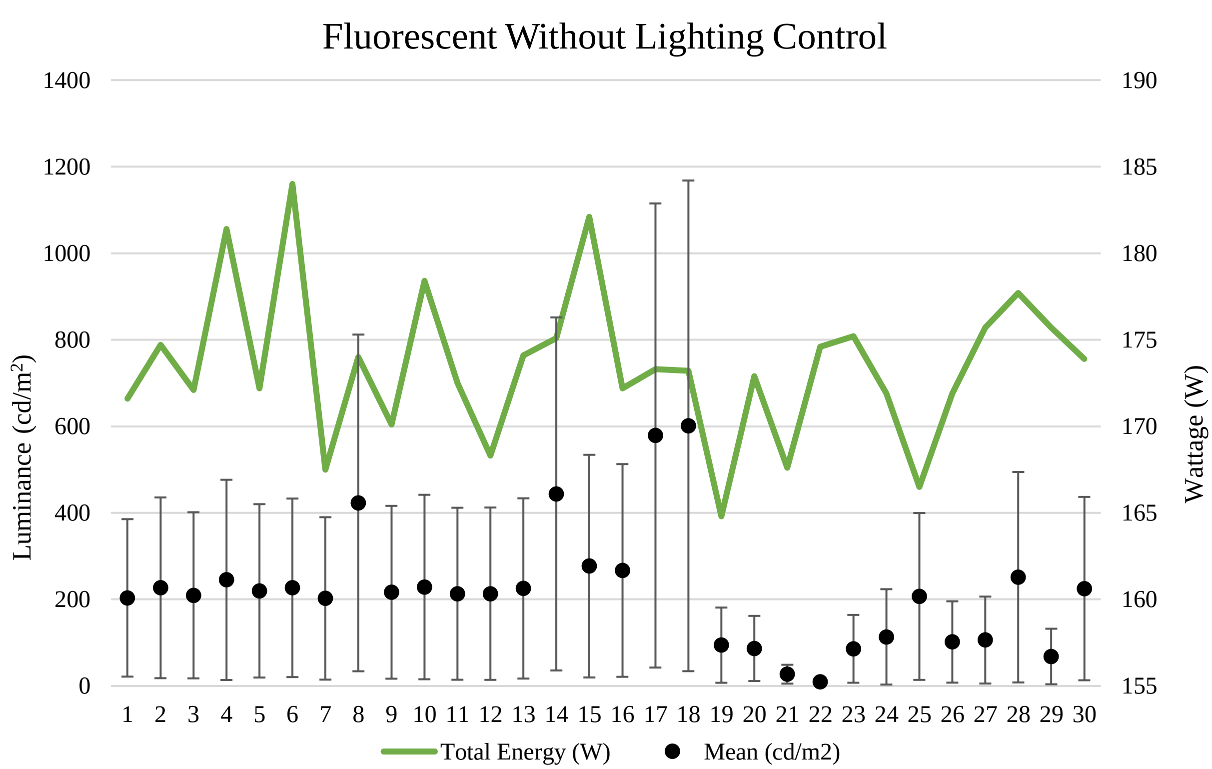
Luminance values obtained from HDR images were graphically analyzed and compared to the total energy usage. Separate graphs were made for each tested lighting condition. Results are shown in Figure 25. For each HDR image, the average luminance was calculated. Error bars were added to each mean value to display the 95% confidence interval. Therefore, 95% of the luminance values obtained from the respective HDR image fall within the range of the error bars. Graphical analysis did not emphasize any consistent relationship between the luminance average of HDR images and the lighting energy usage for either LED or fluorescent lighting systems.



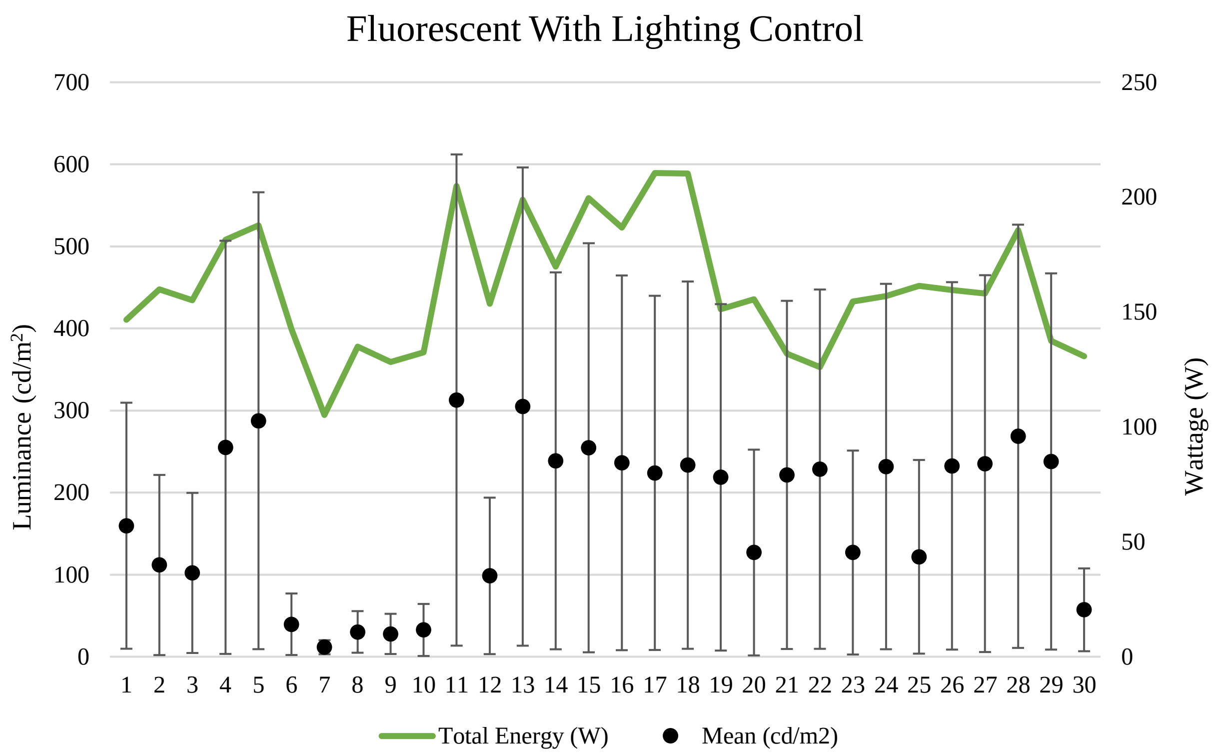
(a)


LED With Lighting Control
1400
1200
1000
800
600
400
200
0
-200
Luminance (cd/m²)
120
100
80
60
40
20
0
Wattage (w)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Total Energy (W)
Mean (cd/m2)

(b)


Fluorescent Without Lighting Control
1400
1200
1000
800
600
400
200
0
Luminance (cd/m²)
190
185
180
175
170
165
160
155
Wattage (W)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Total Energy (W)
Mean (cd/m2)

(c)



(d)

Figure 25: HDR image luminance and total energy usage. (a) LED without lighting control, (b) LED with lighting control, (c) Fluorescent without lighting control, (d) Fluorescent with lighting control

CHAPTER 5 DISCUSSION AND CONCLUSIONS

5.1 DISCUSSION

Several findings were discovered during analysis which may be advantageous to the formation of a lighting design method which merges traditional illuminance-based practice with luminance-based methods. Details of these findings are as follows:

1. Identical recommended illuminance levels can be achieved through a multitude of lighting layouts, but layouts can have varying luminance distribution. The designed layout then has a direct effect on the luminance distribution of the lit space. For this investigation, a total of twelve lighting layouts were designed in AGI32 (six LED layouts and six fluorescent layouts). Illuminance distribution across six sample points were nearly identical. However, the luminance distribution varied between all arrangements. Lighting design methods should account for varying luminance distribution to enhance the quality of the lit environment to meet the needs of space users. In this study, difference in luminance distribution is most notable along vertical surfaces and surface sections closer to the luminaires. Luminance distribution across further planes (e.g., floor) had little notable difference as the light had diffused by the time it reached the surface.
2. A collective decrease in luminance levels was observed when 30 study participants were given access to continuous dimming control for the lighting system. Under LED lighting conditions, over 70% of participants preferred an average luminance level on those eight control points on table top and nearby walls less than 36 cd/m^2. When analyzed over all 30 subjects, average luminance was reduced by 13% once participants were given diming

control. Under fluorescent lighting conditions, over 60% of participants preferred an average luminance level less than 38 cd/m^2. Average luminance of the fluorescent system saw a decrease of almost 5% when analyzed over all 30 subjects.

3. Preferred lighting conditions amongst study participants was given toward decreased general lighting levels and increased task lighting levels when completing office tasks. Over 63% of participants favored these lighting conditions under LED lighting conditions. Under fluorescent lighting conditions, 50% of participants decreased general lighting and increased task lighting to suit their preference. Findings indicate that the direct lighting of tasks holds greater significance in the completion of visual tasks than ambient lighting.
4. Overall energy usage was reduced once participants could adjust lighting to meet their individual preferences. LED lighting reduced the total energy consumption for nearly 77% of participants when given lighting control access. The combined total energy usage of all 30 study participants was reduced by over 18% compared to when subjects were not given lighting control access. Under fluorescent lighting, over 7% reduced total lighting energy consumption was observed for 70% of participant lighting preferences. A lighting design method which caters to human-light interactions has the potential to reduce energy consumption if space users are given individual access to lighting controls.
5. Notable differences in lighting preference based on participant gender or visual acuity could only be moderately identified on a case-by-case basis. Few comparisons made when data was divided by gender or visual acuity could conclude a great difference in correlation. Furthermore, correlation coefficients for the same test under the different

light sources was inconsistent, so further testing is required to analyze if findings are consistent across a larger population.

Findings from this study suggest LED lighting systems can result in lower lighting levels in addition to lower energy consumption than fluorescent lighting systems. When given access to dimming controls, participants seemed to prefer reducing the lighting to lower levels when the LED system was in place when compared to when the fluorescent system was in place. Under the LED lighting system, the average luminance of the eight control points when subjects were given dimming control was 31.6 cd/m^2, a 13% reduction compared to when subjects were not given access to dimming. Comparatively, the average luminance for the fluorescent lighting system was only decreased by 4.7%, once participants were given dimming access, for an average luminance level of 36.6 cd/m^2. Energy data collected when subjects were access to continuous dimming shows the fluorescent system consumed almost three times more energy than the LED system. The fluorescent system consumed 160.6 W while the LED system consumed 55.4 W.

Results of these lower levels directly impact the energy consumption as less power is needed for each luminaire. It is important to note that the dimming capabilities of each light source of different types (LED versus fluorescent) were not analyzed in this study, so the influence of dimming technologies (LED versus fluorescent) on participants preferred luminance level are unknown. Additional research should also be conducted to test for the subjective feelings of space users under both light sources to determine if differences in visual comfort are affected by the light sources.

Results from this study are limited to an individual office space where typing and color clarity are important for task completion. Additional research should be conducted to investigate if the presented findings are consistent and applicable for alternate spaces types of varying size and surface reflectance. In addition, the present study examined only young college students with normal visual acuity. Future research should also be conducted over a greater sample pool of population, which factors in a greater range of ages and visual acuity, to determine if study findings can be applied to more general population.

Findings from this study are limited to spaces absent of daylight. Illumination of both the computer-simulated model room and the actual testing room was achieved solely through electric lighting. Consequently, daylight analysis was omitted from this study. Daylighting could significantly impact the visual comfort of space occupants, individual lighting preferences, and the total amount of energy consumed. Separate analysis which factors in the effects daylight has on the investigated supplemental, luminance-based lighting design method should be performed in the near future.

Luminance values were all calculated by hand using illuminance and surface reflectance as the lighting design and analysis software used in the present study has mixed accuracy on luminance generations. If luminance-based lighting design is applicable to the future of lighting design as a supplemental lighting design method, another luminance calculating software Radiance is strongly suggested.

5.2 CONCLUSIONS

Current lighting design practices heavily revolve around illuminance and illuminance-based metrics. While these methods have been proven reliable, it should be noted that illuminance is not a direct factor of visual perception or performance. However, luminance, which measures the amount of light reflected from an object and transmitted to the eyes of space users, is a direct factor of vision. A lighting design method which merges illuminance and luminance metrics could better benefit space users' productivity and performance, health and well-being, and reduce lighting energy consumption. Computer simulations and HDR imaging technologies are the proposed tools for realizing this supplemental lighting design method.

This study explored the luminance distribution caused by varying lighting layouts, in addition to, the observed patterns and preferences of light levels when 30 participants were given access to continuous dimming control. Analysis of Stage 1 found that luminance distribution for lighting layouts with similar illuminance levels is affected by the layout of the luminaires and the light source. Stage 2 results propose lighting levels recommend are higher than necessary for the completion of visual task. Also indicated in Stage 2 was lighting condition preferences of space users is towards decreased general light levels coupled with increased task lighting levels. Moreover, energy consumption was reduced under both LED and fluorescent lighting systems when human subjects were able to adjust the lighting levels to suit their preferences.

Additional research is needed to investigate if study results are consistent over a wider population and across different types of lighting environments. Investigation into the effects daylighting would have in a supplemental design method were not yet performed.
The research outcomes are therefore considered useful to assist the lighting community in the creation of a supplemental luminance-based lighting design method which better caters to

human-light interactions. The supplemental method has the potential to positively impact society by improving space users' overall satisfaction of the lit environment and reducing the amount of energy consumed by lighting systems. This research at its preliminary stage for developing a new lighting design method is expected to meet the needs of lighting society.

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APPENDICES

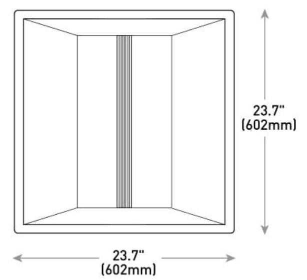
APPENDIX A CREE CR22 LED TROFFER CUTSHEET

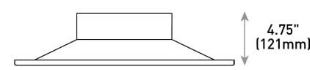
CR Series

CR22™ 2' x 2' Architectural LED Troffer

Product Description

The CR22™ Architectural LED troffer delivers up to 100 lumens per watt of exceptional 90 CRI light at both 2000 and 3200 lumen levels. This breakthrough performance is achieved by combining the high efficacy and high-quality light of Cree TrueWhite® Technology with a unique thermal management design. The CR22™ product family is available in warm, neutral, cool, or daylight color temperatures and has step, 0-10V, or Lutron EcoSystem® Enabled dimming options. Its unique indirect illumination design lightweight design makes the CR22™ perfect for use in commercial new construction or renovated spaces.





NOTE: Use of Expanded Junction Box will expand the depth to 6.67" and Emergency Backup will expand the depth to 6.30". Use of 347V will increase fixture height by 1.4"

Performance Summary

Utilizes Cree TrueWhite® Technology (90 CRI)
Room-Side Heat Sink
Efficacy: 90-100 LPW
Initial Delivered Lumens: 2,000, 3,200 lumens
Input Power: 22-35 watts
CRI: 90 CRI (Cree TrueWhite® Technology), 80+ CRI (HD)
CCT: 3000K, 3500K, 4000K, 5000K
Input Voltage: 120-277 VAC or 347 VAC
Limited Warranty†: 10 years
Limited Warranty Emergency Back Up (EB) Battery: 1 Year Battery Back Up. Test regularly in accordance with local codes
Lifetime: Designed to last from 50,000 hours (HD), 75,000 hours (Standard TW), and 100,000 hours (HE TW)
Controls: Step Level to 50%, 0-10V Dimming or Lutron EcoSystem Enabled to 5%*
Mounting: Recessed**

† See http://lighting.cree.com/warranty for warranty terms
* Reference www.cree.com/lighting for recommended dimming control options
** Acceptable for use with standard 9/16 T-Bar or larger when installed per installation instructions. Consult factory for non-standard grid applications

Accessories

Field-Installed		
Adjustable Cable AC5 72 PD8 JB AC5 18/4 72 PD8 JB **Chicago Plenum Field Kit** CPLCR **Chicago Plenum Field Kit-Emergency** CPLCR EM	**Junction Box** EJBCR 5PK - Expanded size junction box for through wiring (5 pack) **Power Whip** PW 18/4 06 9T/SS CR	**347 Volt** CR 347V **Step Dimming to 50%** CR 347V SD **Surface Mount Kit** SMK CR22

Ordering Information

Example: CR22-20L-35K-S

CR22					
Product	**Initial Delivered Lumens**	**CCT**	**Voltage**	**Control**	**Options**
CR22	**20L**[1] 22W 2000 lumens – 90 LPW **32L** 32W 3200 lumens – 100 LPW	**30K** 3000K **35K** 3500K **40K** 4000K **50K** 5000K	**Blank** 120-277 Volt **34** 347 Volt - Integrated option available on 32L only. Other types require addition of a 347 accessory kit (see table above)	**S** Step Dimming to 50% **10V** 0-10V Dimming to 5% **LES**[2] Lutron EcoSystem® Enabled to 5%	**HD** **CRI 80+ (44W 4000 lumens - 90 LPW)** - Available only with 40L **EB14**[3] **Emergency Backup - 1400 lumens** - Not for use with SMK Kits . Use EB14 SMK **EB14SMK**[3] **Emergency Backup with surface mount kit - 1400 lumens** - Includes surface mount kit accessory (SMK-CR22)

1. Not available with HD 2. Not available in 20L 3. Not available in LES types
NOTE: Price adder may apply depending on configuration

Rev. Date: V5B 12/22/2016

US: www.cree.com T (800) 236-6800 F (262) 504-5415 Canada: www.cree.com/canada T (800) 473-1234 F (800) 890-7507

Product Specifications

CREE TRUEWHITE® TECHNOLOGY

A revolutionary way to generate high-quality white light, Cree TrueWhite® Technology is a patented approach that delivers an exclusive combination of 90+ CRI, beautiful light characteristics, and lifelong color consistency, all while maintaining high luminous efficacy – a true no compromise solution.

CREE LED TECHNOLOGY

Cree's total systems approach to product development is a comprehensive engineering philosophy that combines the most advanced LED sources, driver technologies, optics and forms. The result is highly-reliable luminaire solutions for both indoor and outdoor applications that reduce energy use, extend lifetimes, and maximize illumination performance and quality.

ROOM-SIDE HEAT SINK

An innovative thermal management system designed to maximize cooling effectiveness by integrating a unique room-side heat sink into the diffusing lens. This breakthrough design creates a pleasing architectural aesthetic while conducting heat away from LEDs in a temperature-controlled environment. This enables the LEDs to consistently run cooler, providing significant boosts to lifetime, efficacy, and color consistency.

CONSTRUCTION & MATERIALS

- Durable 22-gauge steel housing with standard troffer access plate for electrical installation
- One-piece lower reflector finished with a textured high reflectance white polyester powder coating creates a comfortable visual transition from the lens to the ceiling plane
- Includes t-bar clips and holes for mounting support wires enable recessed or
suspended installation
- Individual luminaires may be mounted end to end for a continuous row of illumination

OPTICAL SYSTEM

- Unique combination of reflective and refractive optical components achieves a uniform, comfortable appearance while eliminating pixelation and color fringing
- Components work together to optimize distribution, balancing the delivery of high illuminance levels on horizontal surfaces with an ideal amount of light on walls and vertical surfaces. This increases the perception of spaciousness
- Diffusing lens integrated with upward-facing LED strip eliminates direct view of LEDs while lower reflector balances brightness of lens with the ceiling to create a low-glare high angle appearance

ELECTRICAL SYSTEM

- Integral, high-efficiency driver
- **Power Factor:** = 0.9 nominal
- **Input Power:** Stays constant over life.
- **Input Voltage:** 120-277V or 347V, 50/60Hz
- **Operating Temperature Range:** 0˚C - + 35˚C (32˚F - + 95˚F)
- **Total Harmonic Distortion:** < 20%

CONTROLS

- Step dimming to 50%*
- Optional continuous dimming to 5% with 0-10V DC control protocol*
- Optional Lutron EcoSystem® Enabled option allows seamless integration with Lutron EcoSystem controls
- Reference www.creelink.com/exLink.asp?7098214OZ58R34I26620963 for recommended dimming controls and wiring diagrams

REGULATORY & VOLUNTARY QUALIFICATIONS

- cULus Listed
- Suitable for damp locations
- Designed for indoor use
- UL924 (EB14 option)
- DLC qualified. Please refer to www.designlights.org/QPL for most current information
- RoHS compliant. Consult factory for additional details
- Meets FCC Part 15 standards for conducted and radiated emissions

Recommended CR Series Lumen Maintenance Factors (LMF)[1]

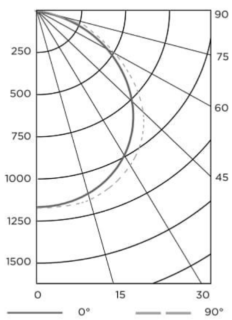
Ambient	Initial Delivered Lumens	Initial LMF	25K hr Projected[2] LMF	50K hr Projected[2] LMF	75K hr Calculated[3] LMF	100K hr Calculated[3] LMF
0˚C (41˚F)	20L and 32L	1.05	1.04	1.04	1.04	1.04
5˚C (41˚F)	20L and 32L	1.04	1.03	1.03	1.03	1.03
10˚C (50˚F)	20L and 32L	1.03	1.02	1.02	1.02	1.02
15˚C (59˚F)	20L and 32L	1.02	1.01	1.01	1.01	1.01
20˚C (68˚F)	20L and 32L	1.01	1.00	1.00	1.00	1.00
25˚C (77˚F)	20L and 32L	1.00	0.99	0.99	0.99	0.99
30˚C (86˚F)	20L and 32L	0.99	0.98	0.98	0.98	0.98
35˚C (95˚F)	20L and 32L	0.98	0.97	0.97	0.97	0.97
40˚C (104˚F)	20L and 32L	0.97	0.96	0.96	0.96	0.96

[1] Lumen maintenance values at 25˚C (77˚F) are calculated per TM-21 based on LM-80 data and in-situ luminaire testing
[2] In accordance with IESNA TM-21-11, Projected Values represent interpolated value based on time durations that are within six times (6X) the IESNA LM-80-08 total test duration (in hours) for the device under testing ((DUT) i.e. the packaged LED chip)
[3] In accordance with IESNA TM-21-11, Calculated Values represent time durations that exceed six times (6X) the IESNA LM-80-08 total test duration (in hours) for the device under testing ((DUT) i.e. the packaged LED chip)

Photometry

CR22-32L-30K BASED ON LTL REPORT TEST #: 24292

Luminaire photometry has been conducted by a NVLAP accredited testing laboratory in accordance with IESNA LM-79-08. IESNA LM-79-08 specifies the entire luminaire as the source resulting in a luminaire efficiency of 100%.



Coefficients Of Utilization – Zonal Cavity Method				
RC %:	80			
RW %:	70	50	30	10
RCR: 0	119	119	119	119
1	110	105	101	98
2	100	92	85	80
3	91	81	73	67
4	84	72	63	57
5	77	64	55	49
6	71	58	49	43
7	66	52	44	38
8	61	48	39	33
9	57	44	36	30
10	53	40	32	27

Effective Floor Cavity Reflectance: 20%

Reference http://lighting.cree.com/products/indoor/troffers/cr-series for detailed photometric data

Average Luminance Table (cd/m²)				
		Horizontal Angle		
		0°	45°	90°
Vertical Angle	45°	3,575	3,864	3,972
	55°	3,164	3,656	3,758
	65°	2,498	3,133	3,347
	75°	1,620	2,348	2,051
	85°	366	252	168

Zonal Lumen Summary			
Zone	Lumens	% Lamp	Luminaire
0-30	923	N/A	28.1%
0-40	1,527	N/A	46.5%
0-60	2,704	N/A	82.5%
0-90	3,280	N/A	100%
0-180	3,959	N/A	100%

Application Reference

Based on CR22-32L-30K Luminaire

Open Space						
Spacing	Initial Delivered Lumens	Lumens	Wattage	LPW	w/ft²	Average fc
8 x 8	22L	2000	22	90	0.35	28
	32L	3200	32	100	0.55	44
8 x 10	22L	2000	22	90	0.28	23
	32L	3200	32	100	0.44	37
10 x 10	22L	2000	22	190	0.22	20
	32L	3200	32	100	0.35	31
10 x 12	22L	2000	22	90	0.19	16
	32L	3200	32	100	0.29	25

9' ceiling: 80/50/20 reflectances; 2.5' workplane, open room. LLF: 1.0 Initial Open Space: 50' x 40' x 10'

US: www.cree.com T (800) 236-6800 F (262) 504-5415 **Canada: www.cree.com/canada** T (800) 473-1234 F (800) 890-7507

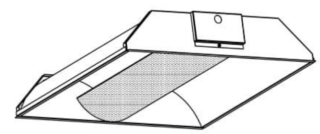
APPENDIX B PHILIPS PERFORM FLUORESCENT TROFFER CUTSHEET

0507.2-AR

Architectural Fluorescent

PerForm

Recessed Direct/Indirect
2x2 1, 2, or 3 lamp
T5, T5HO, T8, or CFTT5



Specifier's Reference

Project	
Type	
Model No.	
Comments	

application

- Economical architectural recessed direct/indirect lighting for glare free illumination.
- Suitable for grid inverted T (NEMA "G") ceilings. Flange type ceilings (NEMA "F") require independently mounted flange kits (FMA).
- Screw slot (NEMA "SS") ceiling models are designed to position the bottom of the luminaire at the ceiling plane.
- Fully recessed mounting, suitable for row mounting.

construction/finish

- Welded housing construction.
- Soft white baked enamel finish.
- Easy ballast access through lamp compartment.
- Grid clips included.

electrical

- Class P, HPF ballasts comply with Ⓔ Federal Ballast Law (Public Law 100-357, 1988).
- UL listed for damp locations. Canadian listing optional.
- Self-contained fluorescent emergency power pack can be incorporated. Some models will require a ballast box on top of the luminaire.

enclosures

- Micro-perforated mesh lamp shield provides soft awareness of light source.
- Soft white overlay on inside of micro-perforated mesh conceals lamp image and balances between reflected and direct light.
- Swing down lamp shield for easy relamping.

accessories

- **FMA22** – 2' x 2' "F" mounting frame for NEMA "F" mounting.

Green Choice: 2PFG217-PMW-UNV-1/2-EBHE-LPT835HL

2 PF ___ ___ ___ – PMW – ___ – ___

Width
2 – 2'

Family
PF – PerForm

Ceiling Type
G – Grid
T – Screw Slot

No. of Lamps
(not included)
1
2
3 (except CF)

Lamp Type/Wattage
14 – 14WT5 (22")
17 – 17WT8 (24")
24HO – 24WT5HO (22")
CF40 – 40WTT5 (24")
CF50 – 50WTT5 (24")
CF55 – 55WTT5 (24")

Shielding
PMW – Peforated metal with white overlay

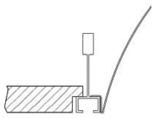
Voltage
120
277
347
UNV – Universal voltage, 120-277 volt

Options
1/1 – One 1-lamp ballast (electronic or non-standard)
1/2 – One 2-lamp ballast (electronic or non-standard)
1/3 – One 3-lamp ballast (electronic or non-standard)
1/21 – 2-lamp & 1-lamp ballasts (electronic or non-standard)
CM – Canadian Market
EB – Electronic ballast, <20% THD
EB10I – Electronic ballast, instant start, <10% THD
EB10R – Electronic ballast, program rapid start, <10% THD
EBD – Electronic dimming ballast
EBHE – T8 electronic ballast, high efficiency, std. ballast factor
EBLHE – T8 electronic ballast, high efficiency, low ballast factor
EBHHE – T8 electronic ballast, high efficiency, high ballast factor
E1 – DEB-1 emerg. ballast (T8 or CF only), 350-450 lumens (UL dry loc.)
E7 – DEB-7 emerg. ballast, 390-700 lumens (UL dry loc.)
E5 – DEB-5 emerg. ballast (T8 or CF only), 1100-1400 lumens (UL dry loc.)
E5ST – DEB-5ST emerg. ballast with self test, 1100-1400 lumens (UL dry loc.)
F1 – Installed flex, 3/8" diameter, 18 gauge, 3 wire, 6'
F2 – Installed flex, 3/8" diameter, 18 gauge, 4 wire, 6'
GLR# – Fusing, fast blow (# = number of ballasts)
LPT735 – Installed T8 lamps, 70+ CRI, 3500K
LPT835 – Installed T5/T5HO/T8/CF lamps, 80+ CRI, 3500K
LPT835HL – Installed T8 or T5 hi lumen lamps, 80+ CRI, 3500K

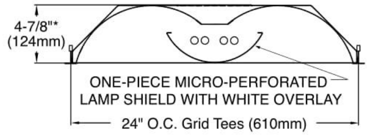
Job pack stretch wrapped w/out cartons - see sheet 1603-OA.
See section 1600-OA for ballast, lamp, and option information.

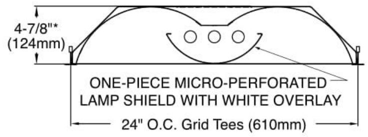
PHILIPS
Day-Brite

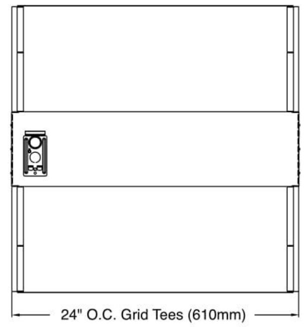
dimensions



Screw Slot







*Models with emergency ballast may require a ballast box on top of luminaire.

photometry

PerForm 2x2 2 Lamp CF40

Efficiency – 69.6% **LER – 59** **TER – 51**

Catalog No.	2PFG2CF40-PMW-1/2-EB
Test No.	26755
S/MH	1.3
Lamp Type	40WTT5
Lumens/Lamp	3150
Ballast Factor	0.88
Input Watts	65

Comparative yearly lighting energy cost per 1000 lumens – **$4.07** based on 3000 hrs. and $.08 pwr KWH.

The photometric results were obtained in the Philips Day-Brite laboratory which is NVLAP accredited by the National Institute of Standards and Technology.

Candlepower

Angle	End	45	Cross
0	1545	1545	1545
5	1538	1536	1538
10	1513	1515	1522
15	1474	1482	1496
20	1419	1439	1460
25	1352	1382	1412
30	1270	1313	1355
35	1173	1233	1289
40	1068	1145	1212
45	952	1046	1123
50	818	936	1020
55	688	821	909
60	551	699	781
65	426	565	635
70	308	428	465
75	207	279	286
80	117	139	168
85	44	56	66

Light Distribution

Degrees	Lumens	% Lamp	% Luminaire
0-30	1202	19.1	27.4
0-40	1972	31.3	45.0
0-60	3495	55.5	79.7
0-90	4385	69.6	100.0

Average Luminance

Angle	End	45°	Cross
45	3623	3981	4274
55	3228	3852	4265
65	2713	3598	4043
75	2152	2901	2974
85	1359	1729	2038

Coefficients of Utilization

EFFECTIVE FLOOR CAVITY REFLECTANCE 20 PER (pfc=0.20)

pcc	80			70			50	
pw	70	50	30	70	50	30	50	30
RCR								
0	82	82	82	81	81	81	77	77
1	76	72	69	73	70	68	68	66
2	68	63	58	67	61	57	58	56
3	63	56	50	60	54	48	52	47
4	57	48	42	56	47	42	46	41
5	53	44	38	51	42	36	41	35
6	48	39	33	46	39	33	38	32
7	45	35	29	44	34	28	34	28
8	41	33	27	40	32	26	30	26
9	39	29	23	38	29	23	28	23
10	36	28	22	35	27	22	27	22

PerForm 2x2 3 Lamp T8

Efficiency – 61.7% **LER – 42** **TER – 36**

Catalog No.	2PFG317-PMW-1/3-EB
Test No.	26746
S/MH	1.3
Lamp Type	F17T8
Lumens/Lamp	1325
Ballast Factor	0.88
Input Watts	51

Comparative yearly lighting energy cost per 1000 lumens – **$5.71** based on 3000 hrs. and $.08 pwr KWH.

The photometric results were obtained in the Philips Day-Brite laboratory which is NVLAP accredited by the National Institute of Standards and Technology.

Additional test numbers available on-line.

Candlepower

Angle	End	45	Cross
0	852	852	852
5	848	846	848
10	837	836	839
15	816	818	826
20	787	794	806
25	752	764	782
30	708	726	750
35	657	683	715
40	598	635	675
45	534	582	631
50	463	523	578
55	388	463	518
60	312	396	450
65	240	324	365
70	173	246	261
75	116	156	157
80	66	78	95
85	26	30	35

Light Distribution

Degrees	Lumens	% Lamp	% Luminaire
0-30	665	16.7	27.1
0-40	1093	27.5	44.5
0-60	1950	49.0	79.5
0-90	2453	61.7	100.0

Average Luminance

Angle	End	45°	Cross
45	2032	2215	2401
55	1820	2172	2430
65	1528	2063	2324
75	1206	1622	1632
85	803	926	1081

Coefficients of Utilization

EFFECTIVE FLOOR CAVITY REFLECTANCE 20 PER (pfc=0.20)

pcc	80			70			50	
pw	70	50	30	70	50	30	50	30
RCR								
0	72	72	72	71	71	71	68	68
1	67	64	61	66	63	60	59	57
2	60	56	52	58	55	51	53	48
3	56	48	44	54	47	42	46	41
4	51	42	38	48	42	38	40	36
5	46	39	33	45	38	33	36	32
6	42	34	28	41	34	28	33	28
7	40	32	26	39	30	26	29	25
8	36	28	23	35	28	23	28	23
9	34	26	20	34	26	20	25	20
10	33	23	19	32	23	19	23	19

PHILIPS

776 South Green Street • Tupelo, MS 38804
p. 800.234.1890 • f. 662.841.5501
Canadian Division
189 Bullock Drive • Markham, Ontario L3P 1W4
p. 905.294.9570 • f. 905.294.9811

Contact Factory for Additional Configurations.
Specifications are subject to change without notice.

Hg

Some luminaires use fluorescent or high intensity discharge (HID) lamps that contain small amounts of mercury. Such lamps are labeled, "Contain Mercury" and/or the symbol "HG". Lamps that contain mercury must be disposed of in accordance with local requirements. Information regarding lamp recycling and disposal can be found at www.lamprecycle.org

APPENDIX C PHILIPS AWARD WINNING LED BULB CUTSHEET

Award Winning LED Bulb

10A19/LPRIZE-PRO/2700-900 DIM 10/1

Philips Award Winning LED Bulb is the efficient, LED alternative to a standard 60 watt incandescent A19 bulb with 800 lumens. The unique bulb design provides omni-directional light with only 10 watts of power.

Product data

• General Characteristics

Cap-Base	E26
Bulb	A19
Bulb Finish	- [-]
Rated Avg. Life (Hours)	30000 hr
Rated Avg. Life (Hours)	30000 hr

• Light Technical Characteristics

Color Code	WW
Color Designation	Warm White
Beam Angle	0 D
Correlated Color Temperature	2700 K
Approximate Lumens	900 Lm
CRI	90
Color Temp. (Kelvin)	2700 K [CCT 2700K]
Rated Luminous Flux	900 Lm

• Electrical Characteristics

Wattage	10 W
Wattage Technical	10.0 W
Voltage	120 V
Dimmable	Yes

• Product Dimensions

Overall Length C	122 mm
Overall Length C [inch]	4.807 (max) in
Diameter D	69 mm

• Product Data

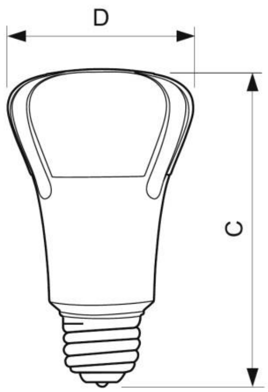
Product number	420224
Full product name	10A19/LPRIZE-PRO/2700-900 DIM 10/1
Short product name	10A19/LPRIZE-PRO/2700-900 DIM 10/1
Pieces per Sku	1
eop_pck_cfg	6
Skus/Case	6
Bar code on pack	46677420222
Bar code on case	50046677420227
Logistics code(s)	929000209704
eop_net_weight_pp	0.120 kg

Dimensional drawing

PHILIPS
sense and simplicity

Award Winning LED Bulb

Dimensional drawing



E26

10A19/LPRIZE-PRO/2700-900 DIM 10/1

Product	C (Norm)	C1 (Max)	D (Norm)	D1 (Norm)
LED 10W E26 2700K 120V A19 DIM	122	4.807	69	2.719

www.philips.com/lighting

2012, December 1
data subject to change

APPENDIX D BULBRITE CFL CUTSHEET

BULBRITE®
turn life on

145 West Commercial Ave.
Moonachie, NJ 07074
T: 800.528.5555
F: 800.441.7708
www.bulbrite.com

15W CFL T3 COIL 2700K DIMMABLE E26 120V
Item #514015
Ordering Code CF15C/WW/DM
UPC 739698514055

- Continuous smooth dimming down to 10% of lumen output
- IC (Integrated Circuit) technology provides longer life when dimming compared to other CFLs
- Ideal for residential and commercial applications

2 Year Warranty · Dimmable · c UL us · lighting facts

TECHNICAL SPECIFICATIONS

Item #	Watts	Bulb Type	Base	Volts	Finish/Description	Beam Angle (°)	Color Temperature (CCT)
514015	15	T3 COIL	E26	120	Frost	N/A	2700K
Color	**CRI**	**Lumens**	**CBCP**	**Average Hours**	**M.O.L. (inches)**	**M.O.D. (inches)**	**Incandescent Equivalent**
Warm White Light	82	900	N/A	10000	4.803	2.126	60W
Energy Star	**DLC**	**Title 24 Compliant**	**Safety Rated**	**Safety Rating Type**	**Enclosed Rated**	**Dimmable**	**Warranty**
N	N	N	UL	DAMP	N	Y	2
Order Multiple QTY							
12							

APPLICATION SUGGESTIONS

Ceiling Fixture · Outdoor Residential · Pendant / Downlight · Portable · Wall Mount / Sconce

APPENDIX E AGI32 CONTROL POINTS ILLUMINANCE DATA

Table E1: LED AGI32 Arrangement Control Points Illuminance Data

	Arrangement 1	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
	Dimmed to 70%	Dimmed to 78%	Dimmed to 68%	Dimmed to 68%	Dimmed to 58%	Dimmed to 68%
Point 1	46.0	44.5	45.8	48.3	47.3	43.8
Point 2	34.7	38.4	36.9	35.1	34.8	40.3
Point 3	42.9	43.5	43.3	44.6	44.5	44.3
Point 4	17.8	16.7	16.7	15.2	16.5	15.4
Point 5	20.8	20.9	18.9	18.3	19.2	19.3
Point 6	18.0	17.1	17.7	17.5	17.9	16.0
Average	30.0	30.2	29.9	29.8	30.0	29.9

Table E2: Fluorescent AGI32 Arrangement Control Points Illuminance Data

	Arrangement 1	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
	Dimmed to 69%	Dimmed to 77%	Dimmed to 67%	Dimmed to 67%	Dimmed to 57%	Dimmed to 67%
Point 1	46.2	44.3	45.8	48.8	47.3	43.6
Point 2	34.6	38.3	36.6	34.9	34.3	40.3
Point 3	42.9	43.4	43.2	44.9	44.3	44.3
Point 4	17.8	17.1	16.5	15.2	16.2	15.4
Point 5	21.1	21.1	19.3	18.9	19.3	19.7
Point 6	17.9	17.0	17.5	17.5	17.4	16.0
Average	30.1	30.2	29.8	30.0	29.8	29.9

APPENDIX F AGI32 ARRANGEMENT SUMMARY DATA

Table F1: AGI32 LED Arrangements Summary Data

Arrangement 1

	Illuminance (fc)					Reflectance	Luminance (cd/m²)		
	Average	Maximum	Minimum	Avg/Min	Max/Min		Average	Maximum	Minimum
Floor	24.17	28.80	17.50	1.38	1.65	0.18	14.59	17.39	10.57
Desk	40.7	46.10	33.50	1.21	1.38	0.12	16.73	18.95	13.77
North Wall	25.33	46.30	14.40	1.76	3.22	0.82	71.58	130.85	40.69
East Wall	21.39	34.20	10.40	2.06	3.29	0.67	49.00	78.35	23.83
South Wall	23.48	41.00	12.80	1.83	3.2	0.27	21.50	37.55	11.72
West Wall	22.36	32.60	14.40	1.55	2.26	0.73	55.91	81.51	36.00

Arrangement 2

	Illuminance (fc)					Reflectance	Luminance (cd/m²)		
	Average	Maximum	Minimum	Avg/Min	Max/Min		Average	Maximum	Minimum
Floor	25.23	30.00	18.40	1.37	1.63	0.18	15.23	18.11	11.11
Desk	41.67	44.60	37.20	1.12	1.2	0.12	17.13	18.34	15.29
North Wall	26.36	41.70	15.10	1.75	2.76	0.82	74.49	117.85	42.67
East Wall	26.18	57.40	12.10	2.16	4.74	0.67	59.98	131.50	27.72
South Wall	24.33	34.90	16.50	1.47	2.12	0.27	22.28	31.96	15.11
West Wall	26.9	41.80	16.10	1.67	2.6	0.73	67.26	104.51	40.25

Arrangement 3

	Illuminance (fc)					Reflectance	Luminance (cd/m²)		
	Average	Maximum	Minimum	Avg/Min	Max/Min		Average	Maximum	Minimum
Floor	23.27	27.70	16.80	1.39	1.65	0.18	14.05	16.72	10.14
Desk	41	45.40	34.80	1.18	1.3	0.12	16.86	18.67	14.31
North Wall	21.91	38.30	11.00	1.99	3.48	0.82	61.92	108.24	31.09
East Wall	21.56	37.20	11.50	1.87	3.23	0.67	49.39	85.22	26.35
South Wall	23.4	40.60	11.80	1.98	3.44	0.27	21.43	37.18	10.81
West Wall	22.13	33.50	13.20	1.68	2.54	0.73	55.33	83.76	33.00

Arrangement 4

	Illuminance (fc)					Reflectance	Luminance (cd/m²)		
	Average	Maximum	Minimum	Avg/Min	Max/Min		Average	Maximum	Minimum
Floor	21.3	25.70	13.00	1.64	1.98	0.18	12.86	15.52	7.85
Desk	41.7	47.70	33.40	1.25	1.43	0.12	17.15	19.61	13.73
North Wall	19.61	37.20	10.10	1.94	3.68	0.82	55.42	105.13	28.54
East Wall	18.25	30.50	8.00	2.28	3.81	0.67	41.81	69.87	18.33
South Wall	20.89	40.00	9.80	2.13	4.08	0.27	19.13	36.63	8.97
West Wall	17.98	26.30	9.60	1.87	2.74	0.73	44.95	65.76	24.00

Arrangement 5

	Illuminance (fc)					Reflectance	Luminance (cd/m²)		
	Average	Maximum	Minimum	Avg/Min	Max/Min		Average	Maximum	Minimum
Floor	21.53	27.20	15.00	1.44	1.81	0.18	13.00	16.42	9.06
Desk	41.67	47.60	33.60	1.24	1.42	0.12	17.13	19.57	13.81
North Wall	19.04	28.10	9.90	1.92	2.84	0.82	53.81	79.41	27.98
East Wall	18.52	36.70	7.00	2.65	5.24	0.67	42.43	84.08	16.04
South Wall	17.67	24.60	8.80	2.01	2.8	0.27	16.18	22.53	8.06
West Wall	19.44	33.80	9.50	2.05	3.56	0.73	48.61	84.51	23.75

Arrangement 6

	Illuminance (fc)					Reflectance	Luminance (cd/m²)		
	Average	Maximum	Minimum	Avg/Min	Max/Min		Average	Maximum	Minimum
Floor	23	28.50	15.90	1.45	1.79	0.18	13.89	17.21	9.60
Desk	42.53	44.30	39.40	1.08	1.12	0.12	17.49	18.21	16.20
North Wall	20.48	27.50	13.10	1.56	2.1	0.82	57.88	77.72	37.02
East Wall	25.94	111.50	8.30	3.13	13.43	0.67	59.43	255.44	19.01
South Wall	17.67	24.60	8.80	2.01	2.8	0.27	16.18	22.53	8.06
West Wall	25.7	80.40	12.30	2.09	6.54	0.73	64.26	201.02	30.75

Table F2: AGI32 Fluorescent Arrangements Summary Data

Arrangement 1

	Illuminance (fc)					Reflectance	Luminance (cd/m^2)		
	Average	**Maximum**	**Minimum**	**Avg/Min**	**Max/Min**		**Average**	**Maximum**	**Minimum**
Floor	24.44	28.90	17.70	1.38	1.63	0.18	14.76	17.45	10.69
Desk	40.67	46.20	33.30	1.22	1.39	0.12	16.72	19.00	13.69
North Wall	26.84	45.60	14.50	1.85	3.14	0.82	75.85	128.87	40.98
East Wall	22.04	34.40	12.30	1.79	2.80	0.67	50.49	78.81	28.18
South Wall	24.83	42.80	15.20	1.63	2.82	0.27	22.74	39.19	13.92
West Wall	23.02	32.90	16.30	1.41	2.02	0.73	57.56	82.26	40.75

Arrangement 2

	Illuminance (fc)					Reflectance	Luminance (cd/m^2)		
	Average	**Maximum**	**Minimum**	**Avg/Min**	**Max/Min**		**Average**	**Maximum**	**Minimum**
Floor	25.49	30.00	18.60	1.37	1.61	0.18	15.39	18.11	11.23
Desk	41.5	44.50	37.00	1.12	1.2	0.12	17.06	18.30	15.21
North Wall	27.98	44.70	15.20	1.84	2.94	0.82	79.07	126.32	42.96
East Wall	26.93	56.90	12.20	2.21	4.66	0.67	61.69	130.35	27.95
South Wall	25.64	36.50	16.60	1.54	2.2	0.27	23.48	33.42	15.20
West Wall	28	46.80	16.10	1.74	2.91	0.73	70.01	117.01	40.25

Arrangement 3

	Illuminance (fc)					Reflectance	Luminance (cd/m^2)		
	Average	**Maximum**	**Minimum**	**Avg/Min**	**Max/Min**		**Average**	**Maximum**	**Minimum**
Floor	23.33	27.70	16.80	1.39	1.65	0.18	14.09	16.72	10.14
Desk	40.93	45.40	34.60	1.18	1.31	0.12	16.83	18.67	14.23
North Wall	23.15	38.50	13.50	1.71	2.85	0.82	65.42	108.80	38.15
East Wall	22.13	37.10	11.50	1.92	3.23	0.67	50.70	84.99	26.35
South Wall	24.72	40.80	14.30	1.73	2.85	0.27	22.64	37.36	13.10
West Wall	22.62	33.60	15.00	1.51	2.24	0.73	56.56	84.01	37.50

Arrangement 4

	Illuminance (fc)					Reflectance	Luminance (cd/m²)		
	Average	Maximum	Minimum	Avg/Min	Max/Min		Average	Maximum	Minimum
Floor	21.49	25.90	13.20	1.63	1.96	0.18	12.97	15.64	7.97
Desk	41.9	48.20	33.20	1.26	1.45	0.12	17.23	19.82	13.65
North Wall	20.97	38.00	11.40	1.84	3.33	0.82	59.26	107.39	32.22
East Wall	18.83	31.10	8.80	2.14	3.53	0.67	43.14	71.25	20.16
South Wall	22.34	40.80	11.90	1.88	3.43	0.27	20.46	37.36	10.90
West Wall	18.53	27.10	11.50	1.61	2.36	0.73	46.33	67.76	28.75

Arrangement 5

	Illuminance (fc)					Reflectance	Luminance (cd/m²)		
	Average	Maximum	Minimum	Avg/Min	Max/Min		Average	Maximum	Minimum
Floor	21.11	25.80	15.00	1.41	1.72	0.18	12.75	15.58	9.06
Desk	41.5	47.70	33.10	1.25	1.44	0.12	17.06	19.61	13.61
North Wall	20.08	30.70	12.30	1.63	2.5	0.82	56.75	86.76	34.76
East Wall	18.91	35.80	8.10	2.33	4.42	0.67	43.32	82.01	18.56
South Wall	18.61	25.60	10.40	1.79	2.46	0.27	17.04	23.44	9.52
West Wall	19.75	32.90	11.00	1.8	2.99	0.73	49.38	82.26	27.50

Arrangement 6

	Illuminance (fc)					Reflectance	Luminance (cd/m²)		
	Average	Maximum	Minimum	Avg/Min	Max/Min		Average	Maximum	Minimum
Floor	22.65	27.80	16.00	1.42	1.74	0.18	13.67	16.78	9.66
Desk	42.43	44.10	39.40	1.08	1.12	0.12	17.45	18.13	16.20
North Wall	21.59	29.90	14.80	1.46	2.02	0.82	61.01	84.50	41.83
East Wall	26.75	117.90	9.40	2.85	12.54	0.67	61.28	270.10	21.53
South Wall	20.02	25.60	12.90	1.55	1.98	0.27	18.33	23.44	11.81
West Wall	28.11	105.90	13.80	2.04	7.67	0.73	70.28	264.78	34.50

APPENDIX G MAJOR SURFACE CALCULATION GRIDS

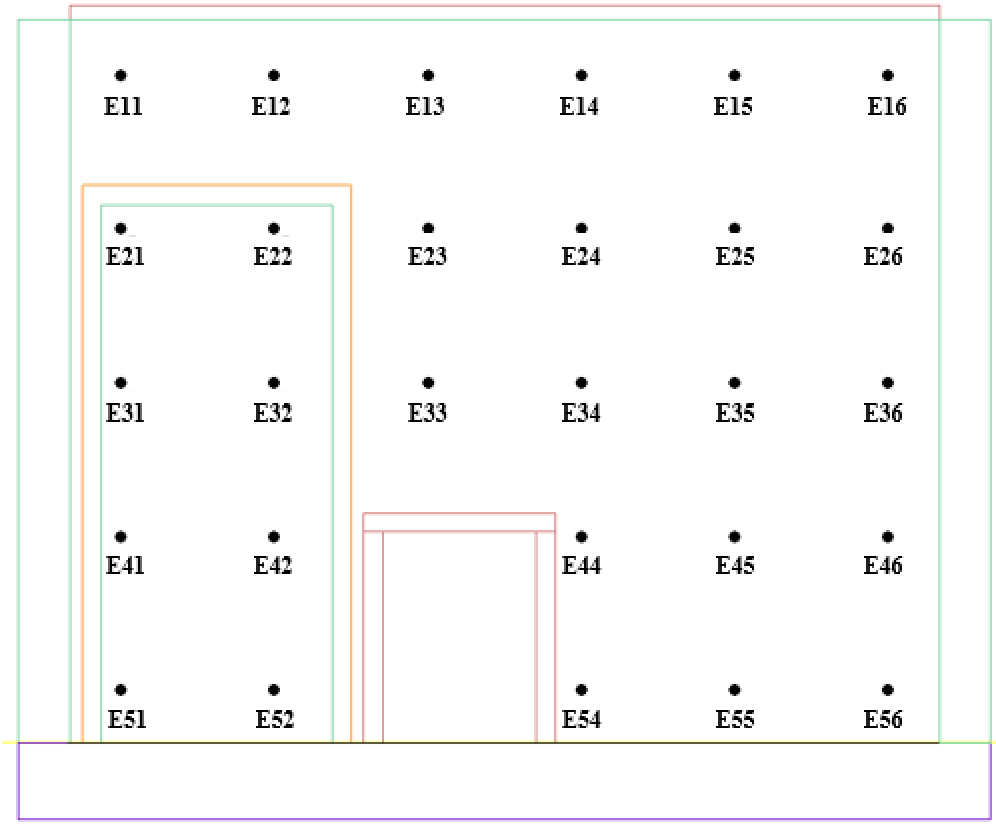


Figure G1: Calculation grid of east wall with measurement points

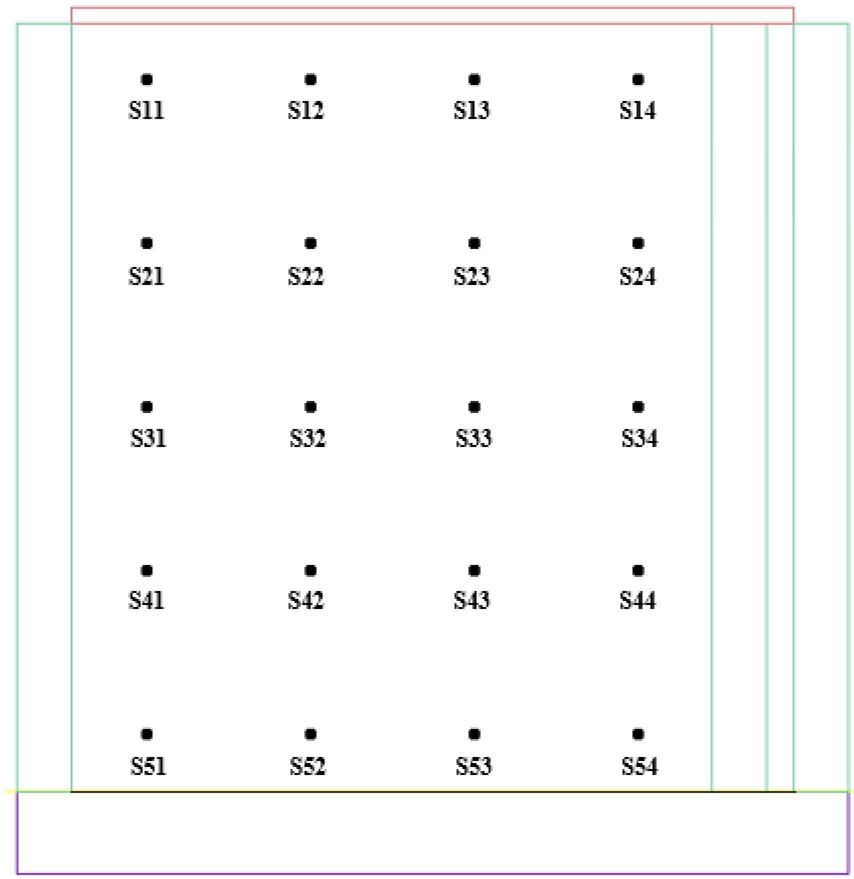


Figure G2: Calculation grid of south wall with measurement points

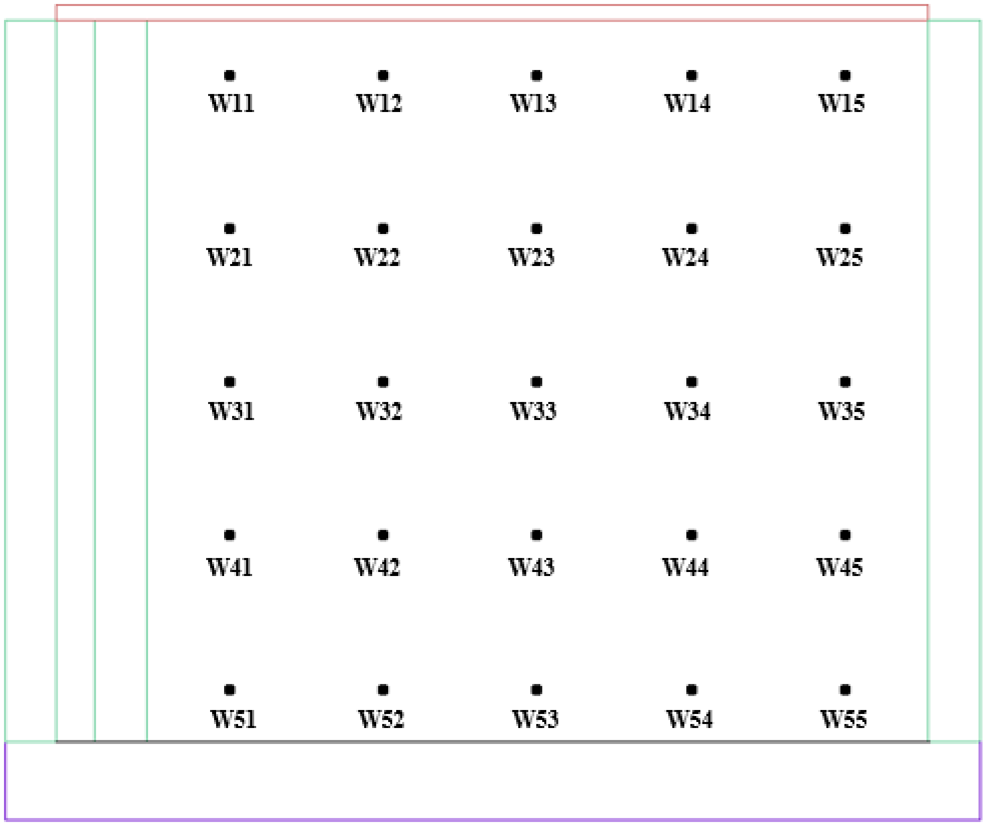


Figure G3: Calculation grid of west wall with measurement points

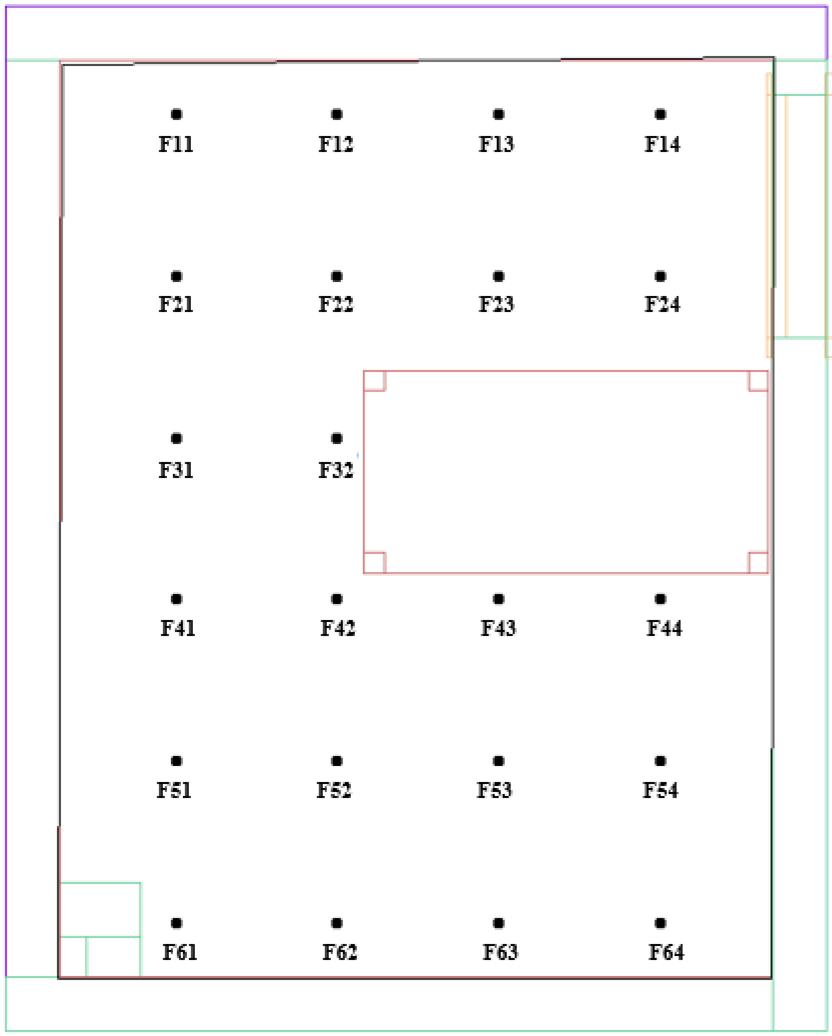


Figure G4: Calculation grid of floor with measurement points

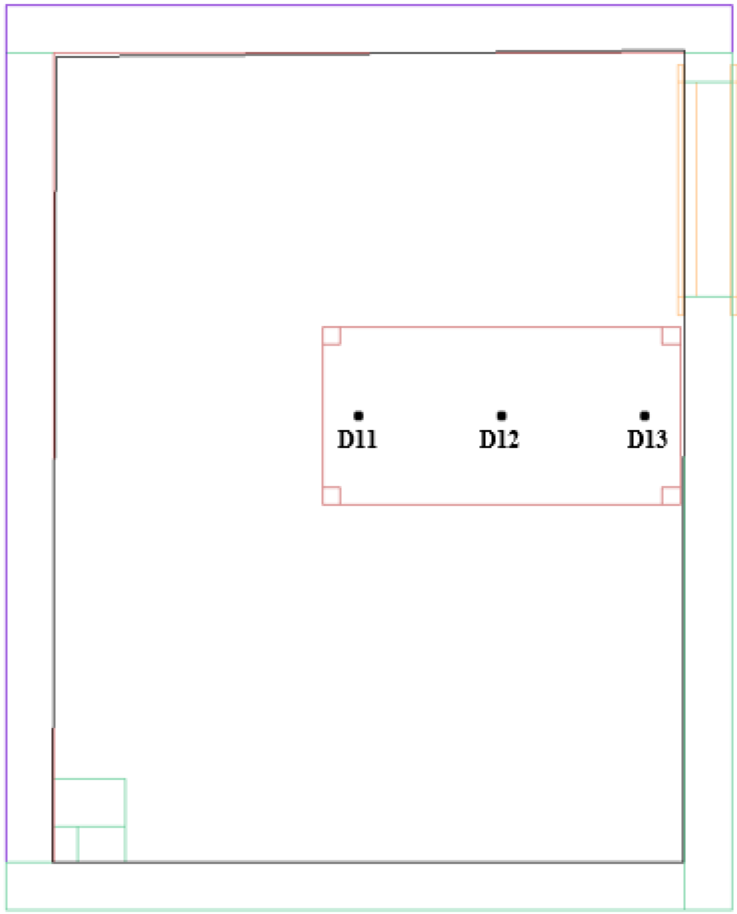


Figure G4: Calculation grid of desk with measurement points

APPENDIX H MEASUREMENT POINTS ON MAJOR SURFACES

Table H1: North wall measurement point data

Table H1(a): Fluorescent illuminance data

	Illuminance (Fc)					
Point	Arrangement 1	Arrangement 2	Arrangement 3	Arrangement 4	Arrangement 5	Arrangement 6
N11	20.6	43.5	24.9	12.0	12.7	17.3
N12	44.9	28.4	36.4	26.5	15.4	17.0
N13	44.8	27.4	17.6	32.5	15.3	16.6
N14	20.2	44.6	13.5	13.0	12.3	16.7
N21	31.1	41.4	32.8	22.1	24.0	29.9
N22	45.6	37.0	38.5	35.5	30.7	28.5
N23	45.4	36.0	30.1	38.1	30.7	27.8
N24	28.9	39.4	23.0	23.5	23.3	27.8
N31	25.8	28.1	25.8	21.5	23.4	26.5
N32	29.6	28.4	27.9	26.2	26.9	26.7
N33	28.9	27.6	26.2	26.6	26.6	25.9
N34	23.4	25.6	22.0	21.2	21.9	24.3
N41	20.9	21.7	20.5	17.2	19.3	21.0
N42	22.1	22.2	21.5	18.8	20.9	21.5
N43	21.2	21.4	20.6	18.5	20.0	20.8
N44	18.3	19.2	18.0	16.0	17.4	18.8
N51	16.3	16.8	15.8	12.4	14.9	16.1
N52	17.6	17.9	17.1	13.4	16.3	17.2
N53	16.8	17.2	16.4	13.0	15.8	16.6
N54	14.5	15.1	14.3	11.4	13.6	14.8

Table H1(b): Fluorescent luminance data

	Luminance (cd/m²)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
N11	58.2	122.9	70.4	33.9	35.9	48.9
N12	126.9	80.3	102.9	74.9	43.5	48.0
N13	126.6	77.4	49.7	91.8	43.2	46.9
N14	57.1	126.0	38.2	36.7	34.8	47.2
N21	87.9	117.0	92.7	62.5	67.8	84.5
N22	128.9	104.6	108.8	100.3	86.8	80.5
N23	128.3	101.7	85.1	107.7	86.8	78.6
N24	81.7	111.3	65.0	66.4	65.8	78.6
N31	72.9	79.4	72.9	60.8	66.1	74.9
N32	83.7	80.3	78.8	74.0	76.0	75.5
N33	81.7	78.0	74.0	75.2	75.2	73.2
N34	66.1	72.3	62.2	59.9	61.9	68.7
N41	59.1	61.3	57.9	48.6	54.5	59.3
N42	62.5	62.7	60.8	53.1	59.1	60.8
N43	59.9	60.5	58.2	52.3	56.5	58.8
N44	51.7	54.3	50.9	45.2	49.2	53.1
N51	46.1	47.5	44.7	35.0	42.1	45.5
N52	49.7	50.6	48.3	37.9	46.1	48.6
N53	47.5	48.6	46.3	36.7	44.7	46.9
N54	41.0	42.7	40.4	32.2	38.4	41.8

Table H2: East wall measurement point data

Table H2(a): LED illuminance data

	Illuminance (Fc)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
E11	16.4	30.2	11.8	10.9	10.5	12.8
E12	18.5	57.4	17.1	13.2	14.4	29.7
E13	15.9	19.3	23.7	13.0	17.1	111.5
E14	15.4	26.1	17.7	12.2	15.0	102.0
E15	14.9	55.5	22.1	10.9	10.4	13.9
E16	10.4	13.8	15.5	8.0	7.0	8.3
E21	29.8	37.0	20.4	22.1	19.9	20.3
E22	34.2	42.7	29.6	28.3	29.3	32.4
E23	30.5	32.3	37.2	30.5	36.7	46.4
E24	30.3	35.0	34.2	29.6	32.6	39.7
E25	29.3	38.0	34.0	25.8	21.2	21.6
E26	20.7	23.2	26.3	18.6	12.9	12.9
E31	26.6	26.3	21.6	21.7	21.1	20.2
E32	29.8	28.9	26.2	26.4	26.7	24.4
E33	29.3	27.8	28.7	28.9	29.8	26.8
E34	28.0	26.7	28.0	27.7	27.3	24.4
E35	25.3	24.4	25.3	23.7	20.8	18.9
E36	20.3	19.5	20.5	18.5	14.7	14.0
E41	21.0	20.5	18.7	16.9	18.0	17.5
E42	23.3	22.4	21.1	19.2	20.6	19.5
E44	20.0	19.1	19.4	17.8	18.1	16.6
E45	20.1	19.3	19.4	17.5	17.1	16.1
E46	16.7	16.3	16.2	14.5	13.4	13.1
E51	15.9	15.9	14.7	11.9	14.1	14.2
E52	15.0	14.9	15.2	12.1	15.3	15.0
E54	12.2	12.1	11.5	8.8	10.1	9.9
E55	15.3	15.2	15.1	12.1	13.5	13.3
E56	13.1	13.1	12.6	10.5	10.9	10.9

Table H2(b): LED luminance data

	Luminance (cd/m²)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
E11	37.6	69.2	27.0	25.0	24.1	29.3
E12	42.4	131.5	39.2	30.2	33.0	68.0
E13	36.4	44.2	54.3	29.8	39.2	255.4
E14	35.3	59.8	40.5	27.9	34.4	233.7
E15	34.1	127.1	50.6	25.0	23.8	31.8
E16	23.8	31.6	35.5	18.3	16.0	19.0
E21	68.3	84.8	46.7	50.6	45.6	46.5
E22	78.3	97.8	67.8	64.8	67.1	74.2
E23	69.9	74.0	85.2	69.9	84.1	106.3
E24	69.4	80.2	78.3	67.8	74.7	90.9
E25	67.1	87.1	77.9	59.1	48.6	49.5
E26	47.4	53.1	60.3	42.6	29.6	29.6
E31	60.9	60.3	49.5	49.7	48.3	46.3
E32	68.3	66.2	60.0	60.5	61.2	55.9
E33	67.1	63.7	65.7	66.2	68.3	61.4
E34	64.1	61.2	64.1	63.5	62.5	55.9
E35	58.0	55.9	58.0	54.3	47.7	43.3
E36	46.5	44.7	47.0	42.4	33.7	32.1
E41	48.1	47.0	42.8	38.7	41.2	40.1
E42	53.4	51.3	48.3	44.0	47.2	44.7
E44	45.8	43.8	44.4	40.8	41.5	38.0
E45	46.0	44.2	44.4	40.1	39.2	36.9
E46	38.3	37.3	37.1	33.2	30.7	30.0
E51	36.4	36.4	33.7	27.3	32.3	32.5
E52	34.4	34.1	34.8	27.7	35.1	34.4
E54	27.9	27.7	26.3	20.2	23.1	22.7
E55	35.1	34.8	34.6	27.7	30.9	30.5
E56	30.0	30.0	28.9	24.1	25.0	25.0

Table H2(c): Fluorescent illuminance data

	Illuminance (Fc)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
E11	18.7	36.9	13.5	12.8	12.3	15.1
E12	21.2	56.8	19.7	15.5	16.7	39.6
E13	18.3	22.8	26.7	15.6	19.8	117.9
E14	17.8	32.1	20.8	14.6	17.3	100.0
E15	17.5	54.2	24.7	13.1	12.1	16.8
E16	12.5	17.5	18.1	10.1	8.1	9.4
E21	30.2	37.1	21.6	23.0	21.2	22.0
E22	34.4	42.2	29.8	28.6	29.7	33.1
E23	31.6	33.7	37.0	31.1	35.8	44.7
E24	31.1	35.2	34.2	30.2	32.1	38.7
E25	29.4	37.1	33.9	25.9	22.0	22.6
E26	21.4	24.1	26.2	19.2	13.9	13.7
E31	26.6	26.2	21.7	21.9	21.2	20.7
E32	30.0	29.1	26.2	26.4	26.3	24.6
E33	29.2	27.9	28.5	28.7	29.1	26.7
E34	28.0	26.8	27.7	27.4	26.6	24.4
E35	25.5	24.5	25.1	23.6	20.6	19.0
E36	20.3	19.8	20.4	18.4	15.0	14.3
E41	21.1	20.5	18.6	16.9	17.8	17.6
E42	23.4	22.5	21.0	19.3	20.4	19.5
E44	20.0	19.1	19.1	17.7	17.9	16.5
E45	20.3	19.3	19.3	17.4	16.9	16.1
E46	16.8	16.3	16.2	14.5	13.4	13.1
E51	16.1	15.9	14.6	12.0	13.9	14.1
E52	15.2	15.0	15.2	12.2	15.2	15.0
E54	12.4	12.2	11.4	8.8	10.1	9.9
E55	15.5	15.2	14.9	12.1	13.3	13.1
E56	13.3	13.0	12.6	10.5	10.7	10.8

Table H2(d): Fluorescent Luminance data

	Luminance (cd/m^2)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
E11	42.8	84.5	30.9	29.3	28.2	34.6
E12	48.6	130.1	45.1	35.5	38.3	90.7
E13	41.9	52.2	61.2	35.7	45.4	270.1
E14	40.8	73.5	47.7	33.4	39.6	229.1
E15	40.1	124.2	56.6	30.0	27.7	38.5
E16	28.6	40.1	41.5	23.1	18.6	21.5
E21	69.2	85.0	49.5	52.7	48.6	50.4
E22	78.8	96.7	68.3	65.5	68.0	75.8
E23	72.4	77.2	84.8	71.2	82.0	102.4
E24	71.2	80.6	78.3	69.2	73.5	88.7
E25	67.4	85.0	77.7	59.3	50.4	51.8
E26	49.0	55.2	60.0	44.0	31.8	31.4
E31	60.9	60.0	49.7	50.2	48.6	47.4
E32	68.7	66.7	60.0	60.5	60.3	56.4
E33	66.9	63.9	65.3	65.7	66.7	61.2
E34	64.1	61.4	63.5	62.8	60.9	55.9
E35	58.4	56.1	57.5	54.1	47.2	43.5
E36	46.5	45.4	46.7	42.2	34.4	32.8
E41	48.3	47.0	42.6	38.7	40.8	40.3
E42	53.6	51.5	48.1	44.2	46.7	44.7
E44	45.8	43.8	43.8	40.5	41.0	37.8
E45	46.5	44.2	44.2	39.9	38.7	36.9
E46	38.5	37.3	37.1	33.2	30.7	30.0
E51	36.9	36.4	33.4	27.5	31.8	32.3
E52	34.8	34.4	34.8	27.9	34.8	34.4
E54	28.4	27.9	26.1	20.2	23.1	22.7
E55	35.5	34.8	34.1	27.7	30.5	30.0
E56	30.5	29.8	28.9	24.1	24.5	24.7

Table H3: South wall measurement point data

Table H3(a): LED illuminance data

	Illuminance (Fc)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
S11	12.8	17.6	19.8	9.8	8.8	10.6
S12	17.8	18.5	29.2	20.6	10.4	12.8
S13	19.2	17.5	15.8	25.3	10.5	13.1
S14	15.2	18.3	11.9	11.3	9.4	11.6
S21	25.0	32.8	32.2	21.5	17.6	20.5
S22	37.3	34.8	40.6	36.2	22.3	22.8
S23	41.0	33.9	32.5	40.0	23.3	23.1
S24	30.9	34.8	24.4	25.0	19.6	21.9
S31	23.8	26.4	25.0	21.1	19.7	21.7
S32	29.7	29.5	290.0	27.0	23.8	24.3
S33	31.4	29.8	28.4	28.0	24.6	24.8
S34	27.0	28.2	24.5	22.9	21.6	23.2
S41	19.8	20.9	19.8	16.9	17.6	19.0
S42	23.0	23.5	22.6	19.7	20.5	21.3
S43	24.0	24.2	23.0	20.2	21.3	21.9
S44	21.9	22.6	21.0	18.1	19.3	20.6
S51	15.7	16.5	15.5	12.4	14.1	15.2
S52	18.1	18.6	17.7	14.0	16.3	17.1
S53	18.8	19.3	18.3	14.5	16.9	17.7
S54	17.6	18.2	17.0	13.4	15.7	16.8

Table H3(b): LED luminance data

	Luminance (cd/m^2)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
S11	11.7	16.1	18.1	9.0	8.1	9.7
S12	16.3	16.9	26.7	18.9	9.5	11.7
S13	17.6	16.0	14.5	23.2	9.6	12.0
S14	13.9	16.8	10.9	10.3	8.6	10.6
S21	22.9	30.0	29.5	19.7	16.1	18.8
S22	34.2	31.9	37.2	33.2	20.4	20.9
S23	37.5	31.0	29.8	36.6	21.3	21.2
S24	28.3	31.9	22.3	22.9	17.9	20.1
S31	21.8	24.2	22.9	19.3	18.0	19.9
S32	27.2	27.0	265.6	24.7	21.8	22.3
S33	28.8	27.3	26.0	25.6	22.5	22.7
S34	24.7	25.8	22.4	21.0	19.8	21.2
S41	18.1	19.1	18.1	15.5	16.1	17.4
S42	21.1	21.5	20.7	18.0	18.8	19.5
S43	22.0	22.2	21.1	18.5	19.5	20.1
S44	20.1	20.7	19.2	16.6	17.7	18.9
S51	14.4	15.1	14.2	11.4	12.9	13.9
S52	16.6	17.0	16.2	12.8	14.9	15.7
S53	17.2	17.7	16.8	13.3	15.5	16.2
S54	16.1	16.7	15.6	12.3	14.4	15.4

Table H3(c): Fluorescent illuminance data

	Illuminance (Fc)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
S11	15.2	22.7	24.2	11.9	10.4	12.9
S12	22.3	22.7	40.7	27.4	12.9	15
S13	25.0	20.6	18.9	36.4	13.2	15.1
S14	18.6	23.5	14.3	13.6	11.4	13.9
S21	25.9	34.3	32.2	22.2	18.9	22.3
S22	39.0	36.4	40.8	37.3	24.4	24.7
S23	42.8	34.8	33.3	40.8	25.5	24.7
S24	32.3	36.5	25.7	25.7	21.3	23.8
S31	24.3	26.9	25.2	21.5	20.2	22.6
S32	30.3	29.9	29.4	27.5	24.6	25.2
S33	31.9	30.2	28.9	28.6	25.6	25.6
S34	27.5	28.4	25.1	23.3	22.3	24.2
S41	20.1	21.2	19.9	17.1	17.6	19.2
S42	23.5	23.8	22.7	20	20.6	21.5
S43	24.4	24.5	23.2	20.5	21.4	22.1
S44	22.3	22.9	21.1	18.3	19.4	20.7
S51	15.9	16.6	15.5	12.4	13.9	15.2
S52	18.4	18.9	17.8	14.1	16.2	17.1
S53	19.1	19.6	18.3	14.6	16.8	17.7
S54	17.8	18.4	17.1	13.5	15.6	16.8

Table H3(d): Fluorescent luminance data

	Luminance (cd/m^2)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
S11	13.9	20.8	22.2	10.9	9.5	11.8
S12	20.4	20.8	37.3	25.1	11.8	13.7
S13	22.9	18.9	17.3	33.3	12.1	13.8
S14	17.0	21.5	13.1	12.5	10.4	12.7
S21	23.7	31.4	29.5	20.3	17.3	20.4
S22	35.7	33.3	37.4	34.2	22.3	22.6
S23	39.2	31.9	30.5	37.4	23.4	22.6
S24	29.6	33.4	23.5	23.5	19.5	21.8
S31	22.3	24.6	23.1	19.7	18.5	20.7
S32	27.7	27.4	26.9	25.2	22.5	23.1
S33	29.2	27.7	26.5	26.2	23.4	23.4
S34	25.2	26.0	23.0	21.3	20.4	22.2
S41	18.4	19.4	18.2	15.7	16.1	17.6
S42	21.5	21.8	20.8	18.3	18.9	19.7
S43	22.3	22.4	21.2	18.8	19.6	20.2
S44	20.4	21.0	19.3	16.8	17.8	19.0
S51	14.6	15.2	14.2	11.4	12.7	13.9
S52	16.8	17.3	16.3	12.9	14.8	15.7
S53	17.5	17.9	16.8	13.4	15.4	16.2
S54	16.3	16.8	15.7	12.4	14.3	15.4

Table H4: West wall measurement point data

Table H4(a): LED illuminance data

	Illuminance (Fc)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
W11	14.4	41.9	13.2	9.6	9.5	12.3
W12	14.9	32.0	18.2	10.6	12.8	54.8
W13	14.7	17.3	16.6	11.4	15.2	80.4
W14	17.4	41.8	19.3	11.8	13.9	44.5
W15	17.1	36.8	18.7	10.7	11.0	13.5
W21	27.9	36.9	24.6	21.9	18.9	19.9
W22	29.7	35.8	32.5	25.1	28.1	35.3
W23	28.8	30.3	32.3	26.3	33.8	46.2
W24	32.6	39.7	33.5	25.3	29.0	35.7
W25	31.0	38.9	31.0	21.4	20.9	21.7
W31	25.1	24.7	23.1	22.2	19.9	18.8
W32	26.8	25.7	26.2	24.7	24.9	22.9
W33	27.8	26.4	27.5	25.8	28.0	25.8
W34	28.8	27.7	27.3	24.7	26.2	24.2
W35	27.4	27.0	25.0	21.7	21.8	20.9
W41	20.3	19.7	19.5	17.5	17.1	16.5
W42	21.5	20.6	20.7	18.6	19.4	18.0
W43	22.5	21.6	21.5	19.3	20.9	19.3
W44	22.9	22.0	21.3	18.9	20.6	19.3
W45	21.7	21.1	19.9	17.3	18.7	18.1
W51	16.1	16.1	15.7	12.5	13.9	13.8
W52	17.1	17.0	16.6	13.3	15.2	14.8
W53	17.7	17.5	16.9	13.4	15.8	15.5
W54	17.9	17.7	16.8	13.3	15.9	15.7
W55	16.8	16.7	15.5	12.3	14.7	14.7

Table H4(b): LED luminance data

	Luminance (cd/m²)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
W11	36.0	104.8	33.0	24.0	23.8	30.8
W12	37.3	80.0	45.5	26.5	32.0	137.0
W13	36.8	43.3	41.5	28.5	38.0	201.0
W14	43.5	104.5	48.3	29.5	34.8	111.3
W15	42.8	92.0	46.8	26.8	27.5	33.8
W21	69.8	92.3	61.5	54.8	47.3	49.8
W22	74.3	89.5	81.3	62.8	70.3	88.3
W23	72.0	75.8	80.8	65.8	84.5	115.5
W24	81.5	99.3	83.8	63.3	72.5	89.3
W25	77.5	97.3	77.5	53.5	52.3	54.3
W31	62.8	61.8	57.8	55.5	49.8	47.0
W32	67.0	64.3	65.5	61.8	62.3	57.3
W33	69.5	66.0	68.8	64.5	70.0	64.5
W34	72.0	69.3	68.3	61.8	65.5	60.5
W35	68.5	67.5	62.5	54.3	54.5	52.3
W41	50.8	49.3	48.8	43.8	42.8	41.3
W42	53.8	51.5	51.8	46.5	48.5	45.0
W43	56.3	54.0	53.8	48.3	52.3	48.3
W44	57.3	55.0	53.3	47.3	51.5	48.3
W45	54.3	52.8	49.8	43.3	46.8	45.3
W51	40.3	40.3	39.3	31.3	34.8	34.5
W52	42.8	42.5	41.5	33.3	38.0	37.0
W53	44.3	43.8	42.3	33.5	39.5	38.8
W54	44.8	44.3	42.0	33.3	39.8	39.3
W55	42.0	41.8	38.8	30.8	36.8	36.8

Table H4(c): Fluorescent illuminance data

	Illuminance (Fc)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
W11	17.3	46.0	15.0	11.5	11.0	14.5
W12	17.5	38.2	21.1	12.8	15.0	68.3
W13	17.1	20.6	19.2	13.7	17.7	105.9
W14	20.0	46.8	22.0	13.9	16.1	58.8
W15	19.7	43.3	21.4	12.5	12.7	16.1
W21	28.5	36.2	24.9	22.5	19.8	20.9
W22	29.9	36.0	32.4	25.8	28.0	35.3
W23	30.1	31.9	32.3	27.1	32.9	44.7
W24	32.9	39.7	33.6	26.0	29.2	35.7
W25	31.4	38.7	31.0	22.2	22.0	23.5
W31	25.3	24.9	23.1	22.2	19.8	19.1
W32	26.8	25.8	26.0	24.5	24.4	22.8
W33	27.7	26.5	27.2	25.6	27.3	25.6
W34	28.8	27.9	27.2	24.7	25.8	24.4
W35	27.4	27.2	25.2	22.0	21.9	21.4
W41	20.4	19.8	19.4	17.5	16.9	16.5
W42	21.5	20.7	20.6	18.6	19.1	17.9
W43	22.4	21.5	21.4	19.2	20.6	19.3
W44	22.9	22.0	21.3	18.9	20.3	19.3
W45	21.8	21.2	19.9	17.4	18.5	18.2
W51	16.3	16.1	15.7	12.5	13.7	13.8
W52	17.2	17.0	16.6	13.3	15.0	14.8
W53	17.7	17.5	16.8	13.5	15.8	15.5
W54	18.0	17.7	16.7	13.3	15.8	15.7
W55	16.9	16.7	15.5	12.4	14.5	14.7

Table H4(d): Fluorescent luminance data

Point	Luminance (cd/m^2) Arrangement 1	Arrangement 2	Arrangement 3	Arrangement 4	Arrangement 5	Arrangement 6
W11	43.3	115.0	37.5	28.8	27.5	36.3
W12	43.8	95.5	52.8	32.0	37.5	170.8
W13	42.8	51.5	48.0	34.3	44.3	264.8
W14	50.0	117.0	55.0	34.8	40.3	147.0
W15	49.3	108.3	53.5	31.3	31.8	40.3
W21	71.3	90.5	62.3	56.3	49.5	52.3
W22	74.8	90.0	81.0	64.5	70.0	88.3
W23	75.3	79.8	80.8	67.8	82.3	111.8
W24	82.3	99.3	84.0	65.0	73.0	89.3
W25	78.5	96.8	77.5	55.5	55.0	58.8
W31	63.3	62.3	57.8	55.5	49.5	47.8
W32	67.0	64.5	65.0	61.3	61.0	57.0
W33	69.3	66.3	68.0	64.0	68.3	64.0
W34	72.0	69.8	68.0	61.8	64.5	61.0
W35	68.5	68.0	63.0	55.0	54.8	53.5
W41	51.0	49.5	48.5	43.8	42.3	41.3
W42	53.8	51.8	51.5	46.5	47.8	44.8
W43	56.0	53.8	53.5	48.0	51.5	48.3
W44	57.3	55.0	53.3	47.3	50.8	48.3
W45	54.5	53.0	49.8	43.5	46.3	45.5
W51	40.8	40.3	39.3	31.3	34.3	34.5
W52	43.0	42.5	41.5	33.3	37.5	37.0
W53	44.3	43.8	42.0	33.8	39.5	38.8
W54	45.0	44.3	41.8	33.3	39.5	39.3
W55	42.3	41.8	38.8	31.0	36.3	36.8

Table H5: Floor measurement point data

Table H5(a): LED illuminance data

	Illuminance (Fc)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
F11	26.1	27.5	24.6	21.6	22.5	24.5
F12	28.2	29.1	26.1	24.1	24.5	25.8
F13	27.7	28.7	25.4	23.8	23.7	25.5
F14	24.0	25.4	22.0	20.7	21.0	22.8
F21	28.3	29.6	26.9	24.6	25.0	27.1
F22	27.5	28.4	26.3	22.1	27.2	28.5
F23	23.0	23.6	21.2	20.0	26.1	27.2
F24	19.8	20.6	18.3	17.1	22.6	24.2
F31	28.8	30.0	27.7	25.7	25.8	27.6
F32	20.8	21.9	20.6	13.0	18.6	20.2
F41	28.0	29.3	27.2	25.6	24.8	26.7
F42	25.5	26.5	24.5	20.9	22.5	23.8
F43	19.8	20.5	18.8	17.8	16.9	17.6
F44	17.6	18.4	16.8	15.6	15.0	15.9
F51	25.4	26.7	24.7	23.4	21.8	23.7
F52	26.8	27.6	26.3	25.5	23.1	24.4
F53	26.0	26.8	26.0	25.2	22.5	23.7
F54	23.5	24.7	24.1	22.6	20.5	22.1
F61	20.6	21.7	19.9	18.7	16.8	18.3
F62	22.4	23.2	21.9	21.1	18.2	19.4
F63	22.2	23.0	22.1	21.1	18.1	19.2
F64	20.0	21.2	20.5	18.9	16.4	17.9

Table H5(b): LED luminance data

	Luminance (cd/m^2)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
F11	15.8	16.6	14.9	13.0	13.6	14.8
F12	17.0	17.6	15.8	14.6	14.8	15.6
F13	16.7	17.3	15.3	14.4	14.3	15.4
F14	14.5	15.3	13.3	12.5	12.7	13.8
F21	17.1	17.9	16.2	14.9	15.1	16.4
F22	16.6	17.1	15.9	13.3	16.4	17.2
F23	13.9	14.2	12.8	12.1	15.8	16.4
F24	12.0	12.4	11.0	10.3	13.6	14.6
F31	17.4	18.1	16.7	15.5	15.6	16.7
F32	12.6	13.2	12.4	7.8	11.2	12.2
F41	16.9	17.7	16.4	15.5	15.0	16.1
F42	15.4	16.0	14.8	12.6	13.6	14.4
F43	12.0	12.4	11.4	10.7	10.2	10.6
F44	10.6	11.1	10.1	9.4	9.1	9.6
F51	15.3	16.1	14.9	14.1	13.2	14.3
F52	16.2	16.7	15.9	15.4	13.9	14.7
F53	15.7	16.2	15.7	15.2	13.6	14.3
F54	14.2	14.9	14.6	13.6	12.4	13.3
F61	12.4	13.1	12.0	11.3	10.1	11.0
F62	13.5	14.0	13.2	12.7	11.0	11.7
F63	13.4	13.9	13.3	12.7	10.9	11.6
F64	12.1	12.8	12.4	11.4	9.9	10.8

Table H5(c): Fluorescent illuminance data

	Illuminance (Fc)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
F11	26.4	27.6	24.6	21.7	22.3	24.4
F12	28.5	29.3	26.2	24.3	24.4	25.8
F13	28.0	28.8	25.5	24.0	23.5	25.4
F14	24.2	25.5	22.0	20.8	20.8	22.7
F21	28.5	29.8	27.0	24.8	24.9	27.1
F22	27.9	28.7	26.5	22.5	25.6	27.1
F23	23.4	23.9	21.4	20.3	22.8	23.9
F24	20.0	20.9	18.4	17.3	19.6	21.2
F31	28.9	30.0	27.7	25.9	25.8	27.8
F32	21.1	24.2	20.7	13.2	18.8	20.4
F41	28.1	29.4	27.2	25.7	24.8	26.8
F42	25.8	26.8	24.6	21.2	22.7	24.0
F43	20.1	20.7	18.9	18.0	17.0	17.7
F44	17.7	18.6	16.8	15.8	15.0	16.0
F51	25.7	26.9	24.7	23.5	21.7	23.7
F52	27.1	27.9	26.4	25.7	23.0	24.3
F53	26.3	27.0	26.1	25.4	22.5	23.6
F54	23.7	24.9	24.0	22.6	20.3	22.0
F61	20.8	21.9	19.9	18.7	16.6	18.2
F62	22.7	23.4	21.9	21.2	18.1	19.3
F63	22.5	23.2	22.2	21.2	18.0	19.1
F64	20.2	21.3	20.5	19.0	16.3	17.8

Table H5(d): Fluorescent luminance data

	Luminance (cd/m^2)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
F11	15.9	16.7	14.9	13.1	13.5	14.7
F12	17.2	17.7	15.8	14.7	14.7	15.6
F13	16.9	17.4	15.4	14.5	14.2	15.3
F14	14.6	15.4	13.3	12.6	12.6	13.7
F21	17.2	18.0	16.3	15.0	15.0	16.4
F22	16.8	17.3	16.0	13.6	15.5	16.4
F23	14.1	14.4	12.9	12.3	13.8	14.4
F24	12.1	12.6	11.1	10.4	11.8	12.8
F31	17.4	18.1	16.7	15.6	15.6	16.8
F32	12.7	14.6	12.5	8.0	11.4	12.3
F41	17.0	17.8	16.4	15.5	15.0	16.2
F42	15.6	16.2	14.9	12.8	13.7	14.5
F43	12.1	12.5	11.4	10.9	10.3	10.7
F44	10.7	11.2	10.1	9.5	9.1	9.7
F51	15.5	16.2	14.9	14.2	13.1	14.3
F52	16.4	16.8	15.9	15.5	13.9	14.7
F53	15.9	16.3	15.8	15.3	13.6	14.2
F54	14.3	15.0	14.5	13.6	12.3	13.3
F61	12.6	13.2	12.0	11.3	10.0	11.0
F62	13.7	14.1	13.2	12.8	10.9	11.7
F63	13.6	14.0	13.4	12.8	10.9	11.5
F64	12.2	12.9	12.4	11.5	9.8	10.7

Table H6: Desk measurement point data

Table H6(a): LED illuminance data

	Illuminance (Fc)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
D11	46.1	44.6	45.5	47.7	47.6	44.3
D12	42.5	43.1	42.9	44.0	43.8	43.9
D13	33.5	37.2	34.8	33.4	33.6	39.4

Table H6(b): LED luminance data

	Luminance (cd/m^2)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
D11	19.0	18.3	18.7	19.6	19.6	18.2
D12	17.5	17.7	17.6	18.1	18.0	18.0
D13	13.8	15.3	14.3	13.7	13.8	16.2

Table H6(c): Fluorescent illuminance data

	Illuminance (Fc)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
D11	46.2	44.5	45.4	48.2	48.6	44.1
D12	42.5	43.0	42.8	44.3	44.6	43.8
D13	33.3	37.0	34.6	33.2	33.7	39.3

Table H6(c): Fluorescent luminance data

	Luminance (cd/m^2)					
Point	**Arrangement 1**	**Arrangement 2**	**Arrangement 3**	**Arrangement 4**	**Arrangement 5**	**Arrangement 6**
D11	19.0	18.3	18.7	19.8	20.0	18.1
D12	17.5	17.7	17.6	18.2	18.3	18.0
D13	13.7	15.2	14.2	13.7	13.9	16.2